**Confidential Information Deleted**

# Report on the Investigation of the Downers Grove Substation Fire

**Presented to:**

**The Staff of the Illinois Commerce Commission**

**By:**

THE LIBERTY CONSULTING GROUP

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# I. Introduction

## A. Background

On Wednesday, August 10, 2005, a fire at Commonwealth Edison's (ComEd's) Downers Grove substation (TDC580) resulted in a service interruption for about 22,000 customers in several western suburbs of Chicago. [redacted]

[redacted]

ComEd was not able to fully restore service from this outage until the afternoon of Friday, August 12, 2005. The intervening period was one of hot summer weather like those days that had preceded the TDC580 outage and ComEd's inability to restore service sooner during the hot weather focused attention on ComEd's power delivery infrastructure capacity.

The Illinois Commerce Commission (ICC) was concerned whether ComEd's substations designed and operated like the Downers Grove substation are capable of providing reliable electric service to customers, whether ComEd's switching capability generally at its substations may be inadequate to provide reliable electric service in the event of total substation loss, and, therefore, whether equipment outages and associated interruptions of electric service at ComEd's substations could place the health, safety and economic well-being of Illinois citizens at risk. The ICC requested that The Liberty Consulting Group (Liberty) investigate matters associated with the TDC580 incident. This report presents the results of Liberty's response to that request.

## B. Objectives

The ICC specified that Liberty should:

(1) Investigate the circumstances and determine the root cause(s) of the Downers Grove substation TDC580 outage in August 2005. That is, determine why TDC580 failed and any relation of that failure to outages at the Fisk and Sawyer substations in June 2005.

(2) Determine whether other substations in ComEd's power delivery system could fail in a way similar to the TDC580 failure.

(3) Determine to what extent ComEd's system is vulnerable to other widespread electric service interruptions due to insufficient switching capacity when an entire substation is lost.

Liberty organized its work and this report in parallel with the above three objectives. Chapter II of this report describes the Downers Grove fire and presents the results of Liberty's root cause analysis. Chapter III presents the results of Liberty's evaluation of substations similar to TDC580 and provides recommendations resulting from Liberty's review of both Downers Grove and similar substations. Chapter III also contains a method of evaluating the risks and placing a priority on work to limit the risks of an event similar to the Downers Grove fire. Chapter IV discusses to what extent ComEd's system is vulnerable to other widespread electric service interruptions due to insufficient switching capacity or other means to restore service when an entire substation is lost. Chapter IV also contains a method to evaluate the risks associated with the total loss of any substation from all potential events, not just cable-space fires.

## C. The Downers Grove Outage

Late Wednesday afternoon, August 10, 2005, one feeder circuit breaker tripped at TDC580. Within 10 minutes, nine additional feeders de-energized and the Operations Control Center lost all control and indication through SCADA[1] from TDC580. Nearly one hour after the initial trip, ComEd operations purposely de-energized the rest of the substation. The approximate 22,000 customers that were without electric service at that point were in Darien (6,500), Downers Grove (6,200), Westmont (4,200), Downers Grove Township (3,100), Woodridge (1,900), and Bolingbrook (300). ComEd restored service to some customers about 2 hours after the initial trip. Service restoration continued at a regular pace for the next 8 hours until ComEd had restored

[1] Supervisory Control and Data Acquisition. The SCADA system allows an operator to control remotely operation of system components. The system also transmits data such as loadings and breaker position to the operator.

about half of the affected customers. Service restoration results then slowed and by the end of the day Thursday, ComEd had returned service to about 14,500 customers. ComEd then restored service to the final 7,000 customers during the afternoon of Friday, August 12. Liberty found that the root cause of the delay in final customer restoration was ComEd's failure to have any plans for an extended loss of a substation.

A failure in a joint that connects two pieces of cable was the initial failure. Liberty found that inadequate quality control of the joint installation was the root cause of the failure. This installation took place sometime during the 1997-1999 period. Prior to the joint failure, the cable had been carrying a very heavy load and had exceeded its normal load limit. The failed joint, which was in the cable space below the switchgear floor of the substation, started a fire involving its cable and neighboring cables. Liberty found that the root cause of the fire was the failure to implement the lessons learned from previous substation fire events. Because of the design and layout of cables in the cable space, the fire spread and affected other circuits as well as substation controls and indications. Once again, Liberty concluded that the root cause of the fire's propagation was ComEd's failure to implement fully the lessons and recommendations from prior events. The fire destroyed the substation's battery and a portion of the switchgear, both located on the main floor of the substation above the cable space where the fire initiated.

It took about one hour for ComEd's operators to de-energize TDC580. However, there were clear indications that this was a necessary action long before it took place. The dispatchers should have known that there was a fire inside the control building of TDC580, that one feeder tripped, that customers served by that feeder had called in trouble reports, and that they had lost all controls and indications from the substation within the first 9 minutes. By 12 minutes after the initial trip, there were clear indications of customers out of service on nine additional feeders supplied by three different buses. Within the next 22 minutes, the Fire Department, which was on site, notified ComEd of the fire, and ComEd's own operator arrived on site and reported the fire. Nevertheless, ComEd did not de-energize TDC580 until after another 23 minutes passed. Liberty concluded that the root cause of the delay in de-energizing TDC580 was the failure to have adequate plans and operator training for such an event.

## D. Summary of Findings and Recommendations

The Downers Grove fire was a significant event for two reasons:

1. It had major consequences, and
2. It should not have happened.

About 22,000 of ComEd's customers lost service. While ComEd restored service to some customers in about two hours, a significant number of customers were without service during hot weather for 44 hours. In addition, ComEd is incurring considerable costs to re-design and re-build the Downers Grove substation.

Had ComEd implemented lesson learned or lessons that it should have learned from prior, similar events, the fire would not have taken place. Even if the fire started, application of lessons learned would have prevented the spread of the fire. Finally, even if the fire propagated, applications of lessons learned would have minimized the damage and hastened service restoration.

Liberty recommends that ComEd improve its root cause analysis methods, operations training, and cable splice installation practices. ComEd should make changes that reduce the vulnerability of substations to events like the one at Downers Grove and develop basic contingency plans for the loss of service from any substation.

# II. The Downers Grove Substation Fire

## A. Background

This chapter reports the results of Liberty's investigation of the circumstances and root causes of the Downers Grove substation TDC580 outage. The ICC also requested that Liberty report on the relation of the TDC580 outage to other substation fires that occurred on the ComEd system. The first main section of this chapter includes a summary of several earlier events, discusses Liberty's root cause analysis method, and provides a critique of ComEd's root cause analysis of the Downers Grove event. The second main section of the chapter presents the results of Liberty's root cause analysis.

### 1. Other ComEd Substation Events

ComEd has experienced other substation incidents that had similarities to the Downers Grove fire. Liberty reviewed reports on these incidents to evaluate the similarities and determine whether ComEd learned from them to reduce the likelihood or consequences of the Downers Grove event. The table below shows the date of these prior incidents and ComEd's report; the following sections discuss each incident.

| | |
|---|---|
| December 27, 1993 | Fire at Pleasant Hill substation, TDC595 |
| February 16, 1994 | Pleasant Hill substation fire report issued |
| July 18, 1996 | Fire at Bartlett substation, TDC574 |
| October 24, 1996 | Bartlett substation fire report issued |
| August 15, 2001 | Fire at Schaumburg substation, TDC253 |
| October 22, 2001 | Schaumburg substation fire report issued |
| June 24, 2005 | Fire at Fisk substation, STA11 |
| August 31, 2005 | Fisk substation fire report issued |

The ICC requested that Liberty also review the Sawyer substation (TSS63) outage that occurred on June 28, 2005.

#### a. Pleasant Hill Substation Fire[2]

##### *(1) Description of the Incident and ComEd's Follow-up Actions*

On December 27, 1993, a fault occurred in one of two adjacent 12 kV cables in the cable space at the Pleasant Hill substation (TDC595). The fault immediately involved the second circuit. The circuit breakers for both circuits tripped three times as there were two reclosing operations. Although relaying and the switchgear operated as designed, arcing caused by the fault ignited the first cable's insulation, which in turn ignited the second cable's insulation and caused the second

[2] Pleasant Hill Substation Fire Report, February 16, 1994, obtained from the ICC Staff.

cable to fail. Reclosing into faults added more energy and may have contributed to the severity of the fire. The fire propagated from the cable faults to other power and control cables that were on a common wall in the cable space. Although only one cable failed initially, the fire affected all 17 circuits fed from TDC595, either because of the fire's collateral damage or because the substation had to be de-energized for fire fighting.

The table below shows the event's timeline.

| | |
|---|---|
| 8:56 a.m. | The first two feeder circuit breakers automatically tripped and locked out. |
| 9:22 a.m. | Area operators arrived on site; a third circuit breaker automatically tripped. |
| 9:28 a.m. | A fourth circuit breaker automatically tripped. |
| 9:33 a.m. | ComEd opened 12kV busses 1, 2, and 3 via supervisory control |
| 9:37 a.m. | ComEd lost supervisory control. |
| 9:42 a.m. | ComEd called the fire department. |
| 9:56 a.m. | Fire department arrived on site. |
| 10:45 a.m. | ComEd used remote switching to de-energize the incoming 138 kV lines. Fire department entered the building. |

The incident caused service interruption to about 21,600 customers, some for up to four hours. After the first two cables faults, two more feeders faulted from the propagating fire. In addition, the heat of arcing and fire damaged or destroyed a control cable pan and its contents.

The fire's collateral damage was limited to the area of the cable space near the initial fault because ComEd had sealed the cable penetrations and had closed the cable space assess hatches before the fire. Restoration times were relatively short because, at that time, the system had sufficient winter capacity to transfer all loads from all Pleasant Hill substation feeders to other substations.

Laboratory analyses performed on the failed cable indicated that moisture contamination in the non-strand-filled, extruded, cross-linked polyethylene (XLPE) cable insulation likely caused the fault. While the fault occurred at a trained bend in the cable, ComEd found that the cable's bend radius within specification. In addition, while the failure was not at a cable joint, ComEd's investigation noted that one joint damaged by the fire, but located about 12 feet from the initial fault, exhibited "carbon tracking, indicating a failure or the start of a cable failure." The investigation team concluded that "tracking seen on the joint was most likely the beginning of the breaking down of the joint and was not involved in the fire except as a victim of the cable insulation burning."

ComEd formed an investigation team, which issued a report on February 16, 1994. The report's recommendations suggested a review of a variety of issues rather than recommending firm actions. The issues identified for review included replacing non-jacketed concentric neutral extruded cross-linked polyethylene insulated (XLPE) cable with jacketed concentric neutral ethylene propylene rubber (EPR) insulated cable, rerouting power cables to reduce congestion, rerouting control cable pans, modifying 12 kV reclosing practices, and auditing conditions in other cable space substations. The report mentioned the application of instantaneous tripping, which reduces arcing energy, to circuit breakers, but dismissed this suggestion because the team thought that there would be insufficient fault current available from a cable space cable fault to operate instantaneous relays.

The Pleasant Hill fire investigation report indicated that ComEd was taking several actions because of this fire and the 1990 Columbus Park substation fire. These included plans to seal all open cable penetrations in other cable space substations, and, in new substations, to build higher ceilings, to install smoke detectors and switchgear firewalls, and to place battery banks in the center of the switchgear floors. In addition, ComEd indicated that it was specifying the use of EPR-insulated cable for new installations and when replacing unjacketed concentric neutral XLPE cable.

*(2) Liberty's Comments*

The Pleasant Hill substation did not have a fire detection system installed in 1993. According to ComEd's 2005 survey, 23 of the 103 substations identified by ComEd as cable space substations still do not have smoke or heat detectors.[3]

It appears that until this incident occurred, ComEd did not recognize that a fault in cable space cable or joint would cause a propagating fire, potentially resulting in a total substation shutdown. If so, ComEd should have taken this incident very seriously because of the similarity of Pleasant Hill to other substations. Because ComEd was able to transfer quickly all Pleasant Hill substation load to other substations, the significance of the fire may not have been recognized.

The relatively short restoration time reflects ComEd's ability to switch the Pleasant Hill winter loads to other substations in a short amount of time. However, a 2005 study of substation switching capability indicates that under certain summer peak load conditions, ComEd would now be able to transfer only about 59 percent of the Pleasant Hill load.[4]

ComEd's distribution operations did not react quickly to the fire. It took 46 minutes before ComEd called the fire department, and 1 hour and 49 minutes before completely de-energizing the substation. Fire fighting could not proceed until ComEd de-energized the substation. The delay may have contributed to the fire's collateral damage. The event should have caused ComEd to realize that it needed better plans and training for dealing with a substation fire. ComEd may have reduced the fire's damage in the cable space if it had de-energized the substation and called the fire department when the operator first arrived at 9:22 a.m.

The investigation report did not make any recommendations related to the joint that the investigation team concluded was beginning to break down. Although the joint did not cause the fault, it should have caused an investigation. It seems obvious that if a cable fault can cause a cable space fire, so could a joint fault.

[3] Response to Data Request # 118.
[4] Response to Data Request #27.

### b. Bartlett Substation Fire[5]

#### *(1) Description of the Incident and ComEd's Follow-up Actions*

On July 18, 1996, a fault occurred in a feeder cable joint in the cable space of the Bartlett substation (TDC574). Arcing and flame from the joint fault caused fire to propagate to the power cables for eight other circuits and a control cable pan, all located on one wall in the cable space. Although only one cable failed initially, the fire affected all 24 circuits, either because of cable damage, switchgear contamination, or because the substation had to be de-energized for fire fighting. Open floor penetrations and access doors allowed air to feed the fire and smoke to contaminate the switchgear.

The table below shows the event's timeline.

| | |
|---|---|
| 10:42 p.m. | The first feeder circuit breaker tripped and locked out. |
| 10:51 p.m. | Eight additional feeders faulted and their breakers locked out. |
| 11:00 p.m. | A Substation Construction & Maintenance manager arrived on site. |
| 11:08 p.m. | ComEd called the fire department. |
| 11:57 p.m. | Circuit switchers opened locally to de-energize substation. |

The incident caused service interruption to about 29,100 customers. Restoration times ranged from 3 to 21 hours. Limited transfer capability contributed to the long restoration times for some customers. ComEd reported that it was able to pick up only about 20 percent of the customers from remote sources.

ComEd retained the services of a consultant to examine the remains of three damaged joints, one of which had faulted to start the fire. Only the connectors remained from two joints, and only about one-third of the joint body remained on the third joint. The consultant did not conclude the cause of the initial fault because the burning destroyed so much of the joint bodies. However, the consultant and ComEd reported that the joint installations did not comply with ComEd standards and that these deficiencies could have led to partial discharge and insulation damage. The deficiencies included:

- non-standard use of copper braid to cover bare concentric strands
- only two crimps on each connector side, rather than three crimps
- excessive spacing between the connector and the cable insulation
- the jacketing did not seal causing copper stranding to corrode
- joints were bent.

Although ComEd did not make any conclusions about the cause of the joint fault, it appears likely that deficiencies in the assembly of the connector caused excessive electrical stress or excessive heat in the joint insulation resulting in insulation failure in one of the three joints.

[5] Response to Data Request #57.

ComEd's investigation team identified issues and made recommendations. Issues included the open penetrations and access hatches, discrepancies from the standards for installing joints (workmanship) including installing the joints in a cable bend, not having specific standards for routing cables in cable spaces, not grounding the cable racks, and whether to reclose on cable faults. The recommendations included assigning the Transmission Systems group to develop an annually funded cable inspection and replacement policy for cable space substations. Other recommendations included the use of fire-retardant concentric neutral jacketed cables, developing standards for installing cable and routing in cable spaces, standards for grounding 12 kV joints within cable spaces, a new cable space feeder protection program (to minimize fire damage), standards for sealing penetrations, a cable space training program for engineering and construction, and criteria for categorizing cable space substations. In the report, ComEd indicated that it was implementing an action plan to minimize the impact of cable space faults. ComEd was to apply the recommendations from the cable fire investigation report to Bartlett and other similar cable space substations. ComEd was to include the planned work in the 1997-1999 capital budgets. It was not clear exactly what this planned work consisted of.

The following paragraphs describe ComEd's follow-up actions in more detail.

### *Cable Space Program*

In 1998, ComEd created and funded a "Cable Space Replacement Program" for five substations.[6] The program called for the use of a cable test called Tan Delta to determine which cable space cables ComEd needed to replace with flame retardant cable. By the end of 1999, ComEd replaced 37 cables in three substations. By the end of 2000, ComEd had replaced 12 additional cables.

In 2002, after the Schaumburg fire (discussed below), ComEd expanded the program into the "Cable Space Pilot Program." It used different cable testing methods, including Tan Delta, Partial Discharge, and Very Low Frequency (VLF) testing. [7]

ComEd tested 287 and replaced 53 cable sections between 1998 and 2005 at 19 cable space substations. Although TDC580 was on the list of cable space substations considered, no testing occurred before the fire. From 1998 to 2004, ComEd spent almost $7.5 million on the testing and replacement of cable space cables. The peak year for this work was 1999, when ComEd spent $4.762 million.[8]

### *Guidelines for Cable Space Improvements*[9]

Also in 1998, ComEd prepared its "Guidelines for TDC/TSS Cable Space Improvements." The purpose of these guidelines was to provide information for including enhancements in designs when adding or replacing equipment in cable spaces to reduce fire and smoke damage resulting from cable or joint fires. It also included a "TDC/TSS Cable Space Checklist" for identifying

[6] Response to Data Request #104.
[7] Response to Data Request #59.
[8] Response to Data Request #59.
[9] Response to Data Request #82.

conditions that increase fire risk in the cable spaces of substations similar to Bartlett and Pleasant Hill. ComEd stopped building cable-space substations in 1995. Therefore, ComEd was to use these guidelines when installing additional circuits or "when working on cable space improvements." The guidelines suggested that:

- Transformer lead cables should be segregated from other transformer lead cables and from bus tie cables
- Bus tie cables should be at least 3 feet from other cables
- No more than 2 feeder cables, or 3 single conductor transformer lead cables should be on one bracket
- Cables should be distributed evenly throughout the cable space
- At least 12 inches should be provided between the top power cables to the bottom of a control cable tray to allow space to install a fire barrier
- No new cable joints are to be installed in cable spaces for new construction
- All vertical cable joints are to be removed and the cable replaced
- All joints in cable bends are to removed and the cable replaced
- Cable-space joints shall be wrapped with two layers of fireproof tape
- Fire-retardant barriers shall be placed on all cable space control cable trays
- Cables racks and the structural steel beams on which the racks are attached shall be bonded to the perimeter ground bus
- Exposed neutral wires on existing cable-space joints shall be bonded to the perimeter ground bus.

*Systems for Sealing Penetrations*[10]

Unsealed cable penetrations at Bartlett contributed to the severity of the fire and to damage to main floor switchgear. In 1996, ComEd prepared standards for sealing cable penetrations with flame resistant silicone, or with mineral wool. In 2002 and again in 2005, ComEd prepared additional standards for sealing floors using an intumescent[11] sealant using a retaining collar and for installing fire-stops in the walls. The 2005 standards are still "Preliminary."

Typically, ComEd has had to seal penetrations during scheduled outages because of unsafe clearances to energized parts inside switchgear. However, ComEd said that its Fire Protection Engineering Group recently determined the materials needed and the procedures for safely filling openings in energized switchgear in cable space substations. ComEd reported that this should eventually become an Engineering Practice.[12]

[10] Responses to Data Request #82, #115, and #119.
[11] Materials that expand in volume when exposed to heat or flames exceeding a specified temperature.
[12] Interviews, September 29, 2005 and December 6, 2005.

*Other Actions*

According to the 2001 Schaumburg fire report, ComEd had installed an enhanced relay scheme at the Bartlett substation that it designed to detect cable space faults and to inhibit reclosing for cable space faults.[13]

ComEd reported that after the 1996 Bartlett fire, it replaced all cables in Bartlett's cable space with fire-retardant jacketed, EPR-insulated, strand-filled, copper-conductor, concentric-neutral cables,[14] and it removed all joints from the cable space.[15]

*(2) Liberty's Comments*

Nine sets of feeder cables faulted in the cable space and their breakers locked out before anyone arrived at the substation. However, because the cable space was ventilated (open penetrations and access hatches), collateral damage caused by smoke might have been reduced if the substation had been de-energized and the fire department called just after the arrival of the maintenance manager, which was only 17 minutes after the initial trip alarm. It took one hour and 15 minutes to de-energize the substation after the initial breaker lock out.

As with the Pleasant Hill fire over two years earlier, ComEd's distribution operations department did not have a cable space fire plan. Although ComEd called the fire department 25 minutes after the fire started, fire fighters could not proceed until area operators arrived nearly 50 minutes later. Apparently, ComEd did not allow the manager who arrived within 17 minutes after the fire started to de-energize the substation. ComEd's recommendations did not include improving on the operations group immediate response to cable space fires. Not having a distribution operations fire plan contributed to the propagation of the fire.

The length of time required to restore some customers indicates that ComEd did not have sufficient emergency energy sources immediately available to minimize outage time for all customers. This problem should have initiated efforts to at least consider and plan for picking up all loads in case of a substation fire. ComEd's recommendations from the Bartlett fire did not include this.

ComEd reported that the root cause of the fire was a joint failure. This actually was an intermediate cause. The actual direct cause was an improperly installed joint. A likely root cause was deficiencies in ComEd's joint installation quality control processes such as training, supervision, and accountability.

After the Bartlett fire, ComEd knew that cable or joint failures could cause cable space fires. It also identified actions necessary to prevent these fires and, apparently except for considering the installation of fire suppression systems, implemented those actions at the Bartlett substations. ComEd also replaced a number of cables with fire-retardant cable under its Cable Space

[13] Response to Data Request #92.
[14] Interview, November 9, 2005.
[15] Response to Data Request #118.

Replacement Program and its Cable Space Pilot Program. However, most of the cable space substations were not included in this program. Liberty's substation inspections and ComEd's recent cable space audit showed that the application of the fire prevention enhancements was incomplete and sporadic.

### c. Schaumburg Substation Fire[16]

#### *(1) Description of the Incident and ComEd's Follow-up Actions*

On August 15, 2001, a joint failed on a 12 kV cable in the cable space of the Schaumburg substation. Because ComEd had closed the cable space hatches and sealed the cable floor penetrations, collateral damage was limited to a 6-foot wide area on one wall.

The table below shows the event's timeline.

| | |
|---|---|
| 12:51 p.m. | Dispatch center received fire alarm and then a 12 kV feeder breaker trip alarm. |
| 1:15 p.m. | Area operator arrived on site and found cable space filled with smoke. |
| 1:45 p.m. | Substation construction and underground crews arrived with fans and began ventilating the cable space. |
| 1:46 p.m. | Another 12 kV feeder circuit breaker tripped, and on-site personnel reported, "the building shook and a transformer roared." |
| 2:30 p.m. | ComEd called the fire department. They arrived on site about three minutes later. |
| 3:14 p.m. | ComEd de-energized the substation. |
| 3:55 p.m. | Fire extinguished. |

The event caused service interruption to 12,500 customers, some for up to 10 hours and 30 minutes. The collateral damage was limited to one area of the cable space near the joint failure because ComEd had previously sealed the floor penetrations and the cable space access hatches were in the closed position before the fire. Although the collateral damage was similar to that in the Pleasant Hill fire, the total restoration took longer this time, at least in part because ComEd could pick up only about 20 percent of the customers from remote sources. ComEd picked up the remaining feeders after it re-energized the substation and completed feeder cable repairs.

According to ComEd's investigation team, "The field assembly process is suspected to have caused the cable insulation to slowly breakdown until the joint failed." The investigators also noted that a copper jumper connected the ends of the concentric neutral across the joint. ComEd's installation standard did not show this jumper.

ComEd's investigation team for this event found that ComEd could have reduced collateral damage if it had put in place control cable pan fire barriers and joint fire wraps as indicated in

[16] Response to Data Request #92.

the 1998 "Guidelines for TDC/TDC Cable Space Improvements."[17] The investigators were also critical of the 100-minute delay from receipt of the fire alarm to calling the fire department. The team was also concerned that each breaker reclosed twice into the faults. As part of the follow-up to the Bartlett cable space fire, ComEd had installed at Bartlett an enhanced relay scheme designed to inhibit reclosing for cable space faults. However, ComEd reported that it had not proven this scheme as effective.[18]

The investigation team recommended that ComEd complete fire protection enhancements at the Schaumburg cable space as indicated in its 1998 guidelines, implement a program and complete high value fire protection improvements in TSS and TDC substations, to suspend reclosing, perhaps via SCADA, at the Schaumburg substation during cable space fires, implement a procedure that requires the fire department be called whenever there is smoke or fire in a substation, issue a safety alert to keep the hatches closed and the fire barriers in place, and issue a bulletin to label "keep closed when not in use" on all cable space hatches.

ComEd indicated that after the Schaumburg fire, it expanded the "Cable Space Pilot Program," prepared additional standards or modified previous standards for sealing cable penetrations, and marked cable space hatches indicating that they need to remain closed when not being used.

After the fire, ComEd did not remove cable joints in the Schaumburg substation. According to ComEd's 2005 audit of cable space substations, Schaumburg has 32 joints on solid dielectric cables in its cable space.[19]

#### *(2) Liberty's Comments*

Even though the investigation team suspected the cause of the fire was suspect field assembly of the joint that failed, it made no recommendations in this area. Improper work practices was the direct cause of the fire and a likely root cause was deficiencies in ComEd's joint assembly quality control processes such as training, supervision, and accountability.

ComEd's distribution operations department still did not have a cable space fire plan. ComEd would have reduced collateral damage and restoration time if it had called the fire department when it received the fire alarm, and if ComEd would have de-energized the substation at 1:15 p.m. when the operator found the cable space was full of smoke. This was 31 minutes before the second feeder cable failed. It took 2 hours and 23 minutes from the fire alarm and the initial trip to de-energize the substation so that the fire department could extinguish the fire in the cable space. Not having an emergency restoration plan was a root cause of the long restoration time.

Not acting in a formal, comprehensive manner on previous lessons learned for the 1993 Pleasant Hill and especially the 1996 Bartlett fires was a root cause of this fire. Although ComEd audited cable space substations in 1994 and 1997, and made some enhancements in some cable space substations, it had not completed the work as part of a formal and centrally tracked cable space

[17] Response to Data Request #82.
[18] Response to Data Request #92, p. 8.
[19] Response to Data Request #118.

program. It was not until after the Downers Grove fire that ComEd inspected cable space substations to identify what it had done and what it needed to comply with the 1998 "Guidelines for TDC/TSS Cable Space Improvements," and the cable penetration sealing standards. Not completing cable-space fire-prevention enhancements at Schaumburg substation was a root cause of the fire. In addition, ComEd again failed to note the effects of a delayed de-energizing of the substation.

### d. Fisk Substation Fire[20]

#### *(1) Description of the Incident and ComEd's Follow-up Actions*

On June 24, 2005, a 138 kV high-pressure, fluid-filled cable joint failed in the west surface tunnel at Fisk substation.[21] A weld in the steel joint sleeve split open from the pressure caused by internal arcing in the cable pipe. The pressure created by the internal arcing and fault current caused a weld to break on the steel joint sleeve. Although relay protection operated properly, oil flowed from the broken cable pipe and ignited. The resulting fire spread throughout three zones of the tunnel. The fire in one zone lasted about 8 hours.

Heat detectors installed in the tunnel shut down the ventilation system and sent an alarm to Transmission Systems Operations (TSO). The TSO acknowledged the alarm and the smoke detectors alarmed [redacted], who called ComEd and the fire department. The fire suppression system was not automatic; it required that fire fighters attach hoses to standpipes. The fire fighters would not fight the fire until ComEd de-energized the Fisk substation. Although fire fighters used water and foam to fight the fire, these actions were not effective until they learned about the standpipes. Only two of the six firewalls indicated on construction drawings were in place, and construction work had breached one of them.

Fire fighters arrived on-site about 8 minutes after the initial fault and the fire alarm report by the [redacted] monitoring service. A ComEd Transmission Underground Supervisor had already arrived. The supervisor immediately notified the TSO about the fire. Fire fighting could not begin until ComEd de-energized the substation. A second transmission cable faulted about nine minutes after the initial fault. About 22 minutes after the fire initiation, the supervisor told the TSO that it needed to de-energize the substation for the fire fighters. The TSO called the distribution Operations Control Center (OCC) to notify them that it was about to de-energize the substation. Conversation and analysis between the TSO and the OCC took 49 minutes. Switching to de-energize the substation took 26 minutes. Overall, it took 80 minutes from the initial alarm to de-energize the substation.

ComEd had removed an automatic Halon fire extinguishing system at the request of the City of Chicago and replaced it with a manual water deluge system that required fire fighters to connect their hoses to standpipes. Neither the fire department nor any on-site ComEd personnel were aware of these standpipes. As reported in the ComEd investigation report, "for several hours, the

[20] Response to Data Request #9.
[21] [redacted] The Fisk tunnels are 6 feet wide by 12 feet high and form a rectangle around the substation that is 200 wide and 700 feet long.

fire department was unaware of the fire suppression system, standpipes, tunnel configurations, and specific materials." ComEd's fire protection engineer made a telephone call about four and one-half hours after the fire started to inform fire fighters about the standpipes. Three tunnel zones were involved in the fire. Fire fighters extinguished the fires in the first two tunnel zones within 20 minutes after the water was available to the stand pipes. However, the fire had damaged the zone 3 standpipe and fire fighters could not use it. They completely extinguished the fire about eight and one-half hours after it had started.

The ComEd investigation team found that the root cause of the fire was joint installation workmanship. The pressed "dimples" in the connecter did not have the proper depth, the connector contained gouges, and the installer had not installed the binder tape properly. The team determined that "the gouges caused high electrical stresses that eventually broke down the insulating tape that resulted in the electrical fault."

ComEd's investigation also found the following contributing causes:

- ComEd had improperly welded the cable pipe joint casing. This caused the fault to become a fire as oil spilled out.
- ComEd did not have a fire emergency plan for Fisk. Station prints were difficult to access, and those needed by first responders were in a stack. ComEd had not informed the fire department of the tunnel configuration or the unmarked standpipes for the fire suppression system. There were no MSDS[22] sheets or details about hazardous materials for fire fighters. [redacted] The fire department estimated that it could have extinguished the fire in 90 minutes if ComEd had provided a fire emergency plan to them.
- Operations command authority was unclear. It took 80 minutes to start fire fighting while the TSO and the OCC were deliberating whether to de-energize the substation.
- Missing tunnel firewalls and removal of the automatic fire suppression system prolonged the fire.
- ComEd had not sampled the faulted joint for dissolved gas analysis (DGA) testing program. This might have allowed ComEd to predict the insulation deterioration before the joint failed.

The fire damaged several transmission cables and ComEd had to replace miscellaneous parts of the pipe cable system. ComEd estimated the cost of the repairs at $11.4 million. The fire caused service interruption to about 52,000 customers because ComEd had to de-energize transmission lines to the [redacted] substations. ComEd restored service to all but 6,480 customers in a little more than two and one-half hours after it de-energized the Fisk substation for the fire fighters. ComEd restored power to the remaining customers in about 24 hours.

ComEd's investigation team identified numerous issues and made recommendations in its August 31, 2005, report. ComEd's investigation team submitted 34 recommendations to senior management. The key recommendations included:

[22] Material Safety Data Sheets, which are OSHA, required hazardous material documents.

- Implement transmission underground splicing and welding quality control.
- Develop comprehensive fire plans for substations and Fisk and Taylor tunnels.
- Review, modify, and implement tunnel construction standards.
- Implement an accountability system to ensure that underground transmission dissolved gas analysis sampling program includes all intended equipment.

ComEd set deadline dates ranging from September 30, 2005, to June 1, 2007, for implementing each of the investigation team's 34 recommendations. ComEd is to implement most of the recommendations by mid-year 2006.[23] The Office of the President is tracking the progress of ComEd's implementation of these recommendations.

*(2) Liberty's Comments*

Joint installation workmanship was a direct cause, not the root cause, of the fire. A root cause of the fire was a deficiency of ComEd's 138 kV cable joint assembly quality control processes such as training, supervision, and accountability. Similarly, improper welding to the joint pipe was a direct cause, not a contributing cause, of the fire. A root cause of the fire was a deficiency of ComEd's 138 kV welding quality control processes such as training, supervision, and accountability.

ComEd's recommendation #24 said to "benchmark with other utilities regarding the application of fire suppression system for Fisk and Taylor underground transmission line tunnels. Make recommendations to the Senior Management Team." Not having an automatic fire suppression system in place was a root cause of the consequences of the fire. If ComEd's reference to "benchmark" means evaluating available fire suppression systems, then this recommendation is reasonable. However, if ComEd's reference to "benchmark" means that it will not do anything if other utilities do not do it, then ComEd's recommendation is unacceptable.

It is possible that if ComEd sealed the tunnels at the location where they connect with the City of Chicago's tunnel, then ComEd could use $CO_2$ or other gas suppression[24] without causing a hazard to city workers. The recommendation should have been to re-install an automatic fire suppression system for the Fisk and Taylor tunnels, if practical.

Another root cause of the consequences of the Fisk fire was ComEd's failure to apply applicable lessons learned from previous fires. Not having comprehensive substation fire plans was a contributing cause of previous substation fires. Having documents easily and safely accessible to first responders and to fire fighters at substation or tunnel fires is necessary for taking appropriate actions. In addition, decision delays by the OCC and TSO were contributing causes in past substation fires. ComEd should have trained, drilled, and provided guidelines to these groups for use when making decisions during substation and tunnel fires and other emergency substation events.

[23] Response to Data Request #14.
[24] Based on the Liberty interview with a Darien fire chief, a non-ozone depleting form of Halon is being developed.

#### e. Sawyer Substation Events

The ICC requested that Liberty review the Sawyer substation (TSS 63) equipment outage that occurred on June 28, 2005. Liberty found that this outage did not involve a fire.

##### *(1) Description of the Incidents and ComEd's Follow-up Actions*

The following events led to the Sawyer equipment outage and the need for voluntary load reduction on June 28, 2005.

June 24 Sawyer was one of the substations affected on June 24, 2005, as the result of the Fisk substation fire. The outages of nine feeders, serving 12,416 customers, or a little less than half of all customers served by Sawyer, occurred during the period between 9:46 p.m. and 10:55 p.m. Customer restoration times ranged from 10 minutes to 1 hour and 10 minutes.[25]

June 25 ComEd de-energized Sawyer transformer TR71 at 2:25 p.m. and kept it down until 7:33 p.m. to complete the switching process to re-energize the transmission line from Fisk. This switching event caused no customer outages.[26]

June 27 A 12 kV bushing faulted at 2:10 p.m., causing transformer TR71 to automatically trip off line.[27] Transformer TR71 loads automatically transferred to TR72, TR73, and TR74.[28] During the first three hours following the TR71 bushing fault, transformers TR72 and TR73 hourly peak loads exceeded normal ratings, but not the emergency ratings. Transformer TR74 peak load did not exceed 91 percent of its normal rating. After the first three hours, all three transformer loads were heavy, but within normal ratings. The bushing failure event caused no customer outages and it does not appear that there is any correlation between the bushing failure and the Fisk outage.[29]

June 28 ComEd de-energized transformer TR74 at 3:36 a.m. so that it could correct a phase-load unbalance problem caused by the TR74 load tap changer (LTC).[30] ComEd transferred transformer TR74's loads to TR72 and TR73, which were already carrying TR71's load. ComEd temporarily[31] repaired the LTC problem and returned transformer TR74 to service at 2:09 p.m. The approximate ten and one-half hour double transformer outage caused peak hourly loading on TR72 to exceed normal rating on four occasions, and on TR73 on two occasions during this period.[32] To reduce loading on these transformers, ComEd deployed five 2

[25] Response to Data Request #236.
[26] Respoinse to Data Request 228.
[27] Response to Data Request #23.
[28] Response to Data Request #23, DGA tests.
[29] Response to Data Request #229.
[30] Response to Data Request #230.
[31] Permanent repairs were completed on November 11, 2005, per Response to Data Request #235.
[32] Response to Data Request #227.

MW portable generators at four locations. ComEd connected three of the five generators to the system and they were on-line between 8:00 a.m. and 1:20 p.m. ComEd readied but did not use the other two.[33] ComEd also implemented its Voluntary Load Reduction (VLR) program during the period between 10:00 a.m. and 6:00 p.m. for 55 of its customers. Voluntary load curtailment reduced about 8 MW of load per hour on the Sawyer transformers during the 8-hour period.[34] Although 55 customers curtailed load for about 8 hours, the double transformer outage caused no customer outages.[35] There did not appear to be any correlation between the LTC problem and the Fisk outage.

June 29 ComEd replaced the 12kV bushing on transformer TR71 and returned it to service at 11:17 a.m. At 2:00 p.m., ComEd opened TR74 12 kV breaker to help regulate bus voltage during the switching to transfer feeder loads from the Crawford substation back to Sawyer. All four transformers, including TR74, were in service at 7:36 p.m. These switching events caused no customer outages.[36]

Dissolved Gas Analysis Testing (DGA)

ComEd performed DGA oil tests during these events to monitor transformer and LTC conditions. On June 27, it performed DGA tests on oil from transformer TR71 and its LTC to verify that the bushing fault had not damaged the transformer or the LTC. On June 28 and June 29, ComEd performed DGA on transformers TR72, TR73, TR74, and their LTCs to monitor the condition of the TR74 LTC and to verify that heavy loading was not damaging equipment. On June 30, ComEd retested the oil from the TR72 LTC because the gases in the June 29 sample of oil had increased. The TR72 LTC gases tested normal on June 30. [37]

*(2) Liberty's Comments*

A number of events occurred at Sawyer from June 24 to June 29. Two were only switching events related to restoring Sawyer to normal configuration following the Fisk substation outage. One event was the automatic de-energizing of a transformer for a 12kV bushing fault. Another event was the manual de-energizing of a second transformer for a LTC problem. The double transformer outage was not related to the Fisk outage. Liberty did not formally review the appropriateness of past maintenance performed on TR71 or on the TR74 LTC. However, ComEd performed DGA tests annually on the TR74 LTC and inspected the LTC last in 1999.[38]

Unfortunately, for a few hours, two of the four transformers at Sawyer were out of service at the same time, causing heavy loading on the two energized transformers. ComEd appropriately responded by relieving load with portable generators and by implementing its VLR program. Fifty-five customers responded to and accepted ComEd's request to curtail load. Although the

[33] Response to Data Request #232.
[34] Response to Data Request #23.
[35] Response to Data Request #230.
[36] Response to Data Request #234.
[37] Response to Data Request #23, DGA tests.
[38] Response to Data Request #231.

loads on the two transformers exceeded the normal summer ratings, the actions taken by ComEd likely prevented the loads from exceeding emergency ratings.

ComEd appropriately used DGA testing to monitor the condition of the four transformers and the LTCs during the two equipment outage events.

Using the VLR program to relieve load has advantages when sufficient time is available to notify qualified VLR participants of the need to curtail load, for ComEd to receive acceptance from the customer, and to complete any switching that needs to be done. Using VLR is a good tool to prevent customer outages that might be needed to maintain the system without exceeding emergency ratings. Participants of the VLR program receive at least a one-hour notice prior to each load response event. [39] When ComEd implements the VLR program, it typically follows the communicated schedule. In this case, load curtailment continued until 6:00 p.m., even though it returned one of the transformers to service at 2:09 p.m.[40] ComEd estimates the start and finish times for the load curtailment and expects participants to schedule their activities accordingly.

### 2. Root Cause Analysis Methods

A root cause analysis (RCA) is a method for finding and correcting the most important reasons for undesired outcomes or performance problems. RCA differs from typical troubleshooting and problem solving in that these efforts seek solutions to specific difficulties, whereas RCA attempts to determine the underlying issues. An RCA can help to seek out unnecessary constraints and inadequate controls. It can help to target corrective action efforts at the points of most leverage. A good RCA is essential in pointing change management efforts in the right direction and finding the core issues contributing to tough problems.

Liberty used the following definitions for its RCA of the Downers Grove fire.

- **Undesired Outcome**: the end result that is the reason for performing the root cause analysis.
- **Direct Cause**: an event that occurred or the condition that existed before the undesired outcome and that directly resulted in that outcome.
- **Intermediate Cause**: an event that occurred or the condition that existed that, combined with the direct cause, resulted in or contributed to the undesired outcome.
- **Contributing Factor**: a condition that did not lead directly to the undesired outcome but which may be important because it made the outcome worse, or a condition that existed which, if different, could have limited the undesired outcome. Elimination of a contributing factor would not have prevented the outcome.
- **Root Cause**: one of the underlying events, conditions, or factors that created or allowed the undesired outcome. A root cause should be specific, something over which management has control, and something for which the analysts can generate effective recommendations.

[39] Response to Data Request #23.
[40] Response to Data Request #233.

A simple example helps to understand these terms. An undesired outcome was that some lights went off in a house. The direct cause was a blown fuse. If the analysis stops here, the resulting recommendation would be to replace the fuse. However, one may determine that an intermediate cause was a loose connection and a contributing factor was the installation of the wiring by an unqualified electrician. Again, stopping the analysis here could result in a decision not to use that electrician again. Continuing the investigation could lead to a root cause of not providing a sufficient budget for important electrical changes in the house. This could lead to an effective recommendation of always using qualified electricians and demanding inspection of installations.

For its Downers Grove RCA, Liberty defined the undesired outcome as the interruption of electric service to a significant number of customers for a significant period. One of the first steps in the analysis was the development of a timeline of events. A detailed timeline, at least in this case, was crucial to a complete understanding of the incident. As additional information became available, Liberty added to and corrected the timeline. This report contains portions of the timeline at various points, such as the short timelines included in the description of prior substation events. Liberty's complete timeline is in Appendix A to this report.

Liberty also defined seven topics that helped to organize the RCA of the Downers Grove fire. The results of the RCA in main section II.B below address each of the following seven topics:

- The Joint Fault
- The Fire
- Fire Propagation
- Bus 5 Switchgear Damage
- Station Battery Fire
- Time to De-Energize Substation
- Lengthy Restoration Time.

## 3. Assessment of ComEd's Root Cause Analysis

### a. Background

Shortly after the Downers Grove fire, ComEd initiated a root cause analysis through the establishment of a Root Cause Investigation (RCI) team. The team's charter was to determine the root cause of the TDC580 fire, review the response to the event, communicate findings throughout Exelon Energy Delivery, and identify action plans and corrective actions that would eliminate similar incidents.[41]

The RCI team had an officer-level sponsor, a designated responsible manager, seven regular team members, and support from subject matter experts and independent investigators.[42] The team had a facilitator from ComEd's Performance Assessment Group who helped them with

[41] Response to Data Request #98.
[42] Response to Data Request #98 and interview, September 27, 2005.

formal and generic aspects of root cause analysis. Typically, the team worked on the root cause analysis four days (Monday-Thursday) a week, and on Fridays returned to their regular duties. ComEd's RCI team prepared a draft report that went through a management review and ComEd's "Challenge" process.[43] On October 31, 2005, ComEd issued its Root Cause Investigation report.[44]

### b. Evaluation

Liberty evaluated the RCI report to determine whether ComEd appeared headed in the right direction in terms of understanding and taking actions as a result of the TDC580 fire. It is good utility practice that ComEd recognized the significance of the event and dedicated the resources required for a root cause analysis. ComEd assigned a sufficient number of well-qualified personnel to the team. Members held positions in substation engineering, underground construction, planning, cable and equipment specialties, and analysis of operational data. The team also used experts in fire protection and fire investigation.

The RCI report contained 34 numbered recommendations, which at least touched on many of the subjects that are important to the event. Liberty notes, however, that several of the recommendations are very similar and ComEd could have combined them.[45] An appendix to the report provides an analysis of ComEd's restoration of electric service. This appendix is a concise and informative summary of the restoration efforts. It contained sound recommendations (in addition to those in the body of the report) that dealt with Site Restoration Management (SRM) process improvements, dispatch and switching process improvements, mobile substation strategy, and generator deployment.

Despite these good qualities, Liberty concluded that the RCI's report had significant deficiencies. Most important was the fundamental statement of the root cause, which was "12kV circuit W805 joint connector was not pressed to a sufficient crimp diameter resulting in a joint failure."[46] Root cause analysis is a tool used not only to identify what and how an event happened, but also and most importantly why it happened. The root cause(s) should be one of usually multiple correctable factors (conditions, actions, or inactions) that created or contributed to the direct cause and the undesired outcome. Root causes are specific underlying causes that management has control to fix and that are those for which management can implement effective recommendations for preventing recurrences. In contrast, direct causes are those conditions or actions that existed or occurred immediately before the undesired outcome and that, if different or modified, would have prevented the undesired outcome. ComEd's statement of the root cause was a direct cause, not a root cause. This is more than a matter of terminology. Thorough analysis of the event and determination of the actual root causes will lead to recommendations that address the true causes of an incident, not just the visible effects.

[43] The Challenge process includes internal, multi-disciplinary review meetings to discuss things like proposed projects and reports such as this one.
[44] Response to Data Request #128.
[45] For example, #1 suggests implementing infrared thermography and #2 suggests completing infrared testing.
[46] Response to Data Request #128, page 13.

To be more specific, and as examples, the RCI report mentions its review of previous fire investigation reports, but only recommends (not in a numbered recommendation) that "the Company review these previous recommendations."[47] Apparently, the RCI team either did not consider or ruled out the possibility that ComEd's failure to implement properly valid lessons learned from previous, similar events could be one of the real root causes of the current event. The RCI's statement of the root cause did not go beyond the insufficient crimping of the failed joint to ask why this happened, what conditions in terms of training and qualifications existed to permit the insufficient crimping, and whether those conditions presently exist.

The RCI report did not define the undesired outcome that it analyzed. If it identified that outcome as lengthy customer interruptions, the team may have placed more emphasis and possibly offered one or more root causes on the conditions and actions that permitted the time and extent of substation damage and thus the length of service interruptions.

The RCI report did not make definitive conclusions in some areas. For example, the report stated that operators did not have local control at TDC580 because of the loss of control power.[48] It also recommended that someone determine whether operators could open local circuit switchers manually when under load or fault conditions.[49] It seems reasonable that the RCI's efforts should have drawn this matter to conclusion and made specific findings in this regard. As another example, the report was weak in its statements regarding circuit W640, which W805 supplied and caused heavy loading. The report does not mention that the Customer Service Representative (CSR) on duty mis-categorized the call from the Fire Department as an event that did not require immediate attention,[50] that a fire alarm at the OCC is a priority 2 alarm, or that dispatcher's actions during the event were problematic.[51] Finally, the report prefaces all of its recommendations with the statement that they are conditioned on comparable industry benchmarking. Taken literally, this means that the team would only suggest implementing its recommendations if other utilities do it that way. While benchmarking can provide useful information, ComEd should take more of a lead role in determining what good utility practice is, rather than simply following the practices of others.

## B. Root Cause Analysis

### 1. The Joint Fault

#### a. Background

A joint on phase C of feeder W805 in the cable space at the Downers Grove substation failed. The failure ignited a fire that spread to other cables, the Bus 5 switchgear, and the substation battery. ComEd assembled the joint using a [redacted] Company cable joint kit, on a jacketed, copper

[47] Response to Data Request #128, page 3.
[48] Note, however, that the TSO always had the ability to de-energize the substation.
[49] Response to Data Request #128, page 9 and page 22.
[50] Response to Data Request #159, page 2.
[51] Interviews of 9/28/05 and 10/13/05.

concentric neutral, aluminum conductor, 750 MCM[52] cable.[53] A heat-shrink re-jacketing sleeve manufactured by the [redacted] Company covered the joint. The ignition temperature of cable jacket and the joint jacket is about 350° C.[54] Because of a 1999 change in its work management software, ComEd was not able to determine when and who installed the joint.[55] However, because the cable's manufacturing date was 1997, the installation likely occurred between 1997 and 1999.

Since the 1980s, ComEd used joint kits for its concentric neutral cable manufactured by two companies, the [redacted] Company and the [redacted] Company.[56] Although this fire started with a [redacted] joint, [redacted] joint faults started both the 1996 Bartlett and the 2001 Schaumburg cable space fires. ComEd has a large number of the both types of joints in its manholes, typically three joints for each set of feeder cables in each manhole. In comparison, there are relatively fewer joints in substation cable spaces.

The installation of a cable joint involves crimping a connector to the cable ends. The installer uses a hydraulic press, applying up to about 10,000 psi via a hose to a set of dies mounted in a press head, to form the crimp. Although both 750 MCM and 1000 MCM dies fit the press head, inspection of the crimps indicated that ComEd used the proper 750 MCM die set.[57] The press automatically releases after completing its pressing cycle, and then the operator releases the start/stop button.[58] The proper pressing method is to apply three crimps on each end of the connector, starting from the center, and rotating each crimp by about 90 degrees. A proper pressing causes the connector to become longer and with smooth flash.[59] It is possible that an incomplete pressing operation caused the improperly crimped connector. Another potential cause was that the connector material was too hard to obtain sufficient crimping. However, ComEd reported that, regardless of whether the crimp was improper because of a pressing problem, or because the connector was excessively hard, ComEd should expect installers to identify and reject improperly crimped connectors.[60]

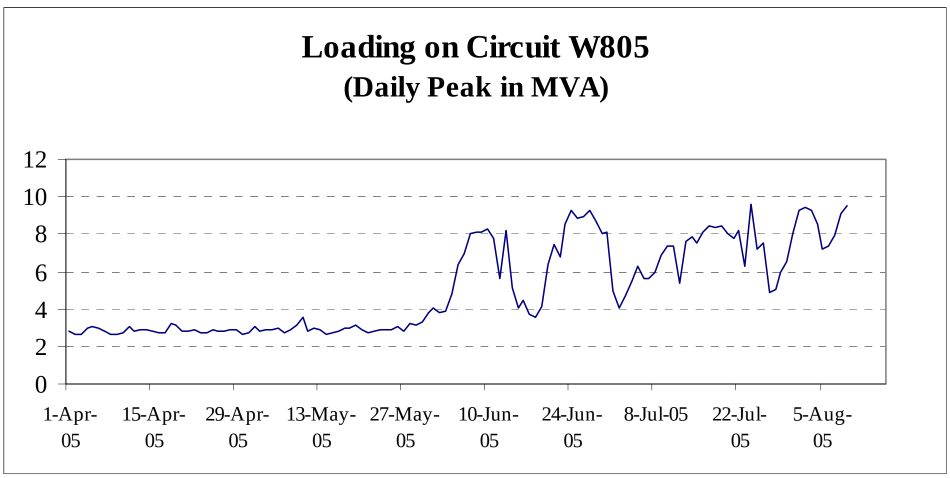
ComEd had had a problem with 750 MCM connectors supplied with [redacted] Company joint kits. In 1997, ComEd underground personnel noticed that some connectors included in their [redacted] joint kits did not crimp properly. The indentations were too shallow and the flash that squeezed out of the connector after pressing was sharp-edged and needed filing. During the resultant investigation, the [redacted] Company informed ComEd that it had supplied a batch of joint kits with connectors that were not annealed, and therefore excessively hard.[61] ComEd retrieved over 500 connectors from joint kits from that batch from storerooms and trucks, and [redacted] tested them for hardness. From those retrieved, ComEd exchanged 441 for annealed connectors.[62] ComEd was

[52] MCM is one thousand circular mils. This is a way of measuring the cross-section of a large conductor.
[53] Interview, September 14, 2005.
[54] Interview, October 10, 2005.
[55] Response to Data Request #164.
[56] Interview, October 10, 2005.
[57] Interview, October 10, 2005.
[58] Response to Data Request #181.
[59] Flash is the material that squeezes out from the die impressions.
[60] Interview, October 12, 2005.
[61] Response to Data Request # 176.
[62] Response to Data Request #218.

not able to determine if it had installed any of the hard connectors in its power delivery system, nor whether the failed joint at Downers Grove was one of these connectors.[63] However, ComEd said that it is continuing its investigation to determine whether the connector involved with the feeder W805 fault was defective when received by the joint supplier.

Circuit W805 had been heavily loaded numerous times before the fault. On May 29, 2005, a fault occurred on Circuit W640, which the Woodridge substation normally feeds. ComEd transferred the W640 load to Downers Grove circuit W805.[64] ComEd repaired the W640 substation exit cable on June 29, June 30, and August 5. In each case, the cable failed the high potential tests and ComEd could not energize it.[65] Because of these multiple faults, ComEd replaced the W640 exit cable but did not return it to service until September 12, 2005, more than a month after the Downers Grove fire. From May 29 to August 10, 2005, the loading on W805, phase C, exceeded its normal rating on 19 occasions, for an accumulated time of 128 hours since May 29.[66] The loading on W805 never exceeded the cable's emergency rating. ComEd reported that the priority level to repair W640 changed several times during the time when W805 carried its load.[67] Operators at the OCC monitor feeder loading via the SCADA system, and engineering and planning are able to analyze feeder-loading history using ComEd's PI-Historian program. However, ComEd did not have guidelines for identifying, notifying, and prioritizing actions needed to relieve feeder loading for ComEd's operations, engineering, and construction departments. Although the overloading may have not caused a properly crimped connector to fail, the bad connector may not have failed if ComEd had not exceeded the cable rating for 128 hours.[68]

The chart below shows the W805 loading prior to August 10.[69] The normal rating is about 7.9 MVA and the emergency rating is about 11.2 MVA.




[63] Interview November 9, 2005.
[64] Response to Data Request # 100.
[65] Response to Data Request # 100.
[66] Liberty derived from ComEd's Response to Data Request #89.
[67] Response to Data Request # 89.
[68] The connector may have failed anyway at some point in the future.
[69] Response to Data Request #89.

### b. Analysis

ComEd could have prevented the failure of the W805 phase C cable joint if it had properly installed the connector in the joint. The improper connection produced sufficient heat to distort the joint insulation and caused the fault. The crimp impressions were too shallow and not properly rotated. It appeared that the installer realized the crimps were improper because the installer crimped one spot twice. There are other indications of an improper crimping, such as differences in the length of the pressed connector and how the material, or flash, squeezes out of crimp impressions. Regardless of whether the base problem was improper installing techniques or an improperly annealed connector, an intermediate cause of the joint fault was the installer's failure to reject the connector before installing the rest of the joint. A root cause is ComEd's inadequate quality control of the joint installation process.

Another cause of the joint fault was loading conditions. The loading on phase C of feeder W805 had exceeded the normal rating many times between May 29 and August 10. It did not exceed its emergency rating. Although numerous loading in excess of normal loading would not have caused a properly installed connector to overheat and cause a joint to fail, a poorly pressed connector could overheat during periods of heavy loading. One of the root causes of the joint fault is ComEd's lack of cable loading guidelines that consider off-normal configurations and durations.

The third possible cause of the joint fault is that ComEd did not include cable space joints in the substation thermographic inspection program. It is possible that ComEd could have identified the bad joint before it failed, particularly if the overload situation had prompted ComEd to perform a special inspection.

The following presents Liberty's assessment of the direct, intermediate, and root causes of the joint failure.

*A1. A direct cause of the joint fault was an improperly crimped connector.*

ComEd's installer did not properly crimp the connector in the failed joint. The depths of the crimp impressions on this connector were noticeably less than those in the connectors in other two phases, and the installer did not rotate the crimps properly. Oxidation was present on the inside surface of the connector indicating that the connector had overheated. Inspection of the remaining portion of the joint insulation indicated that the insulation had deformed, indicating that it had overheated over a period. This deformation from excessive heat over time caused the joint insulation to fail.

*A2. An intermediate cause of the joint fault was the failure of the installer to reject the improperly crimped connector.*

The inadequate depth of the crimps on the connector in the failed joint was caused by either defective pressing equipment, improper operation of the equipment, or an excessively hard connector. However, the installer failed to identify this and other defects. The installer's failure to reject the crimped joint was a cause of the joint failure.

*A3. A root cause of the joint fault was ComEd's inadequate quality control of the joint installation process.*

Underground workers receive six weeks of classroom training and one year of on-the-job training before ComEd allows them to install joints without direct supervision. Because improperly installed joints have caused fires at three cable space substations, it appears that this training has not been sufficient, or an unqualified person installed the joint. ComEd does not have a formal process for assuring that it properly installs every joint. If ComEd had appropriately trained and supervised the installer, the installer would have rejected the improperly crimped connector, and the joint would not have failed.

*A4. Contributing factors related to the joint fault may be the manufacturer's failure to anneal the connecter or an incomplete crimp pressing operation.*

ComEd had a problem with inadequate annealing of 750 MCM connectors supplied with [redacted] Company joint kits. While an improperly crimped connector caused the joint failure, excessive hardness may have contributed to the improper crimp. Also possible is simply an incomplete pressing operation by the installer.

*A5. A direct cause of the joint fault was ComEd's heavily loading of feeder W805.*

Loading on phase C feeder W805 exceeded the feeder's normal summer rating on 19 occasions between May 29 and August 10 for a total of 128 hours. This occurred because ComEd transferred feeder W640's load to feeder W805 during this period.

*A6. An intermediate cause of the joint fault was the extended time that ComEd allowed feeder W640 load to remain on feeder W805.*

ComEd's multiple attempts to repair faults on the W640 exit cable at Woodridge substation delayed ComEd's decision to replace this cable. ComEd did not apply the highest priority to the replacement of this cable.

*A7. A root cause of the joint fault was ComEd's the lack of feeder loading guidelines for this type of situation. Effective guidelines could have improved coordination between operations, engineering, and construction, and provided for the appropriate priority on repairing W640.*

The OCC monitors feeder loading, and PI-Historian load history is available. ComEd operated the cable within its design limits. However, ComEd does not have guidelines that indicate what to do when heavy feeder loading occurs because of an abnormal configuration. The accumulated W805 feeder loading in excess of normal rating likely caused excessive heating in the defective phase C connector.

*A8. A direct cause of the joint fault was undetected overheating of the joint.*

The connector overheated over a period causing the insulation to fail. ComEd could have measured the joint temperature using infrared thermographic inspection when the feeder loading exceeded normal summer rating.

ComEd has been performing annual infrared inspections to identify overheated connections in its substation switchyards since 2000.[70] However, it was not until the Downers Grove fire that it started performing these inspections on joints in cable spaces. As of December 15, 2005, ComEd has identified eleven suspicious connections in cable space substations.[71] Although including the feeder W805 joints in the Downers Grove cable space in its substation infrared inspection program would not have prevented overheating, it may have made ComEd aware of a connection problem, particularly if it had specifically inspected cable space joints while their loadings were high.

*A9. A root cause of the joint fault was ComEd's failure to recognize the ability of infrared thermographic inspection to detect overheated cable space joints.*

Infrared thermographic inspections identify overheated connections. ComEd either failed to recognize the potential benefits of performing these inspections on cable space joints or made a business decision not to perform the inspections in cable spaces. Cable spaces are "confined spaces," requiring extra labor to inspect.

## 2. The Fire

### a. Background

Arcing from the W805 cable joint fault caused the cable jacket to ignite.[72] All cables on the racks above circuit W805 burned and created a large amount of smoke and made the air at the southeast cable space ceiling extremely hot. The fire burned the control cable pan just above the burning power cables, the insulation of the cables in the pan, and the insulation of exposed battery leads.

The fire ignition temperature for all jackets on the concentric neutral cables, including the fire-retardant cables, and joints is about 350˚ C, much less that the 5000° C produced by arcing from an electrical fault. However, the material used in fire-retardant jackets produces low smoke and water when burned and does not promote fire propagation.[73] Open penetrations in the cable space ceiling provided a path for oxygen to the fire.

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[70] Interview, December 6, 2005.
[71] Interview, December 15, 2005.
[72] The [redacted] Company heat shrink joint jacket material burns at about 350° C. A test performed at the Chicago [redacted] facility on September 23, 2005, demonstrated that the material could ignite and continue to burn from a joint fault.
[73] Response to Data Request #102.

The phase C cable joint failure ignited the cable heat-shrink jacket material. ComEd may have prevented the resultant fire if it had wrapped the cables with fire resistant material. The root cause is ComEd's inadequate implementation of known fire prevention enhancements at the Downers Grove substation cable space. ComEd developed these enhancements using lessons learned from previous cable space fires. Contributing factors related to the initial fire include the fact that ComEd had not replaced the joint and that the joint heat-shrink jacket was sufficiently flammable to ignite from fault arcing.

#### b. Analysis

The following presents Liberty's assessment of the direct, intermediate, and root causes, and contributing factors of the fire.

*B1. The direct cause of the initial fire was the joint fault.*

Investigations for the fires at Bartlett in 1996 and at Schaumburg in 2001 indicated that joint faults also caused those cable space fires.[74] The [redacted] tests also indicated that joint faults could set joint heat-shrink jackets afire.[75] ComEd's Downers Grove investigation concluded that failed joint connector led to the cable W805 jacket fire.[76]

*B2. An intermediate cause of the initial fire was ComEd's failure to place fire wrap on the cable joint.*

ComEd had not wrapped the W805 cable joint with fire resistant material as indicated in the 1998 fire prevention guidelines.[77] If ComEd had wrapped the joint, it is likely that any fire would have been contained within the joint, only those customers on feeder W805 would have lost electric service, and ComEd would have shortened the service interruption duration significantly.

*B3. The root cause of the initial fire is ComEd's inadequate implementation of lessons learned.*

Before the 2005 fire, ComEd had not appropriately applied fire prevention enhancements to the Downers Grove cable space that it identified after the 1996 Bartlett cable space fire and included in the 1998 "Guidelines for Cable Space Improvements," and in standards specifically on wrapping cable joints and surrounding cables with fire resistant materials.[78]

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[74] Responses to Data Requests #57 and #92.
[75] Liberty witnessed tests on September 23, 2005.
[76] Response to Data Request #RA01.01, Root Cause Investigation, page 3.
[77] Response to Data Request #82.
[78] Response to Data Request #82.

*B4. A contributing factor related to the initial fire was ComEd's failure to remove the cable space joint.*

Even though cable joint faults caused two previous substation cable space fires, ComEd did not have a program to remove joints. However, ComEd did not allow new joint installations in cable spaces.[79] When ComEd replaces cable space joints, it also replaces the first section of the exit cable, from the breaker to the first manhole. ComEd started using fire-retardant, jacketed feeder cables in its cable spaces after the 1996 Bartlett fire, and standardized on fire-retardant cables in 2000. One feeder ultimately involved in the Downers Grove fire had a fire-retardant jacket and did not contribute fuel to the fire. Although the fire ignition temperature of fire-retardant jackets is about the same as non-fire-retardant jackets, when this material burns it produces water, which prevents the fire from propagating.

*B5. A contributing factor related to the initial fire is the flammability of the joint jacket material.*

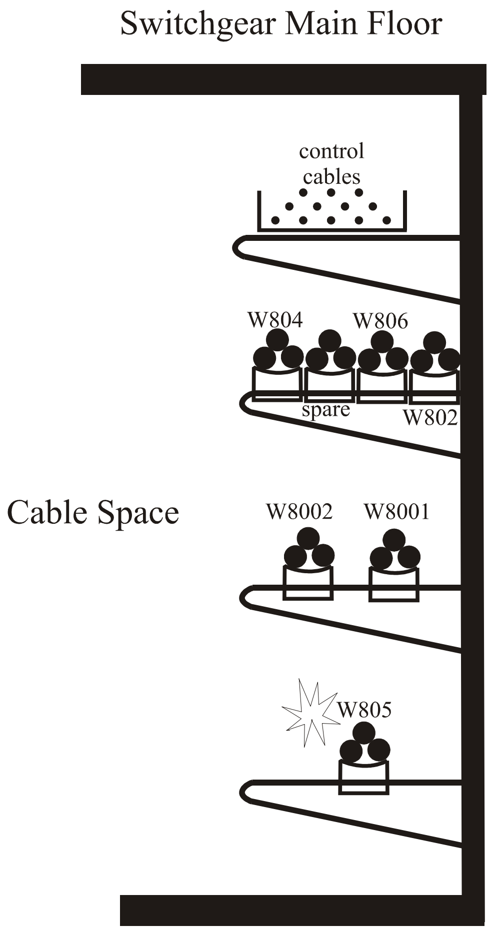
The heat-shrink re-jacketing sleeves installed over joints have an ignition temperature of about 350° C, which is similar to cable jackets. However, joint fault tests conducted by [redacted] showed that arcing from joint faults could set joint materials afire. Electrical arcing produces temperatures over 5000° C. ComEd recognized this after the 1996 Bartlett fire, which a joint fault caused. In 1998, it developed a guideline and standards to prevent cable space fires, which it had not fully implemented at the Downers Grove substation before August 2005

## 3. Fire Propagation

### a. Background

After the jacket on feeder W805 cable joint ignited, the fire spread to other feeder cables, control cables, the Bus 5 switchgear, and eventually started a secondary fire that destroyed the station battery. The diagram below shows the layout of the cables near the faulted joint.

[79] Response to Data Request #82. Liberty found one set of new joints installed in a cable space on November 3, 2005, at the Nordic substation.




Flame from the initial fire ignited cables just above it. One of these cables (W8002) was the only cable involved that was a cross-linked polyethylene (XLPE) insulated cable.[80] The polyethylene insulation fueled the fire, along with polyethylene cable jackets on the ethylene propylene rubber (EPR) cables. When additional cables faulted, the resulting arcing fed the fire and increased the temperature at the top of the confined space. The fire burned the control cable pan just above the fire, the insulation of the cables in the pan, and the insulation of exposed battery leads. The battery leads shorted and burned apart. At 4:39 p.m., ComEd lost SCADA power.

As the fire spread among the cables, cable jackets and insulation fed the fire. Arcing occurred as each cable failed, burning up to several feet of copper shield conductors on each faulted cable, intensifying the flames and heat in the southeast corner of the cable space. The intense flame and heat burned away a section of the control cable pan and burned the control cables. The fire burned and shorted the battery bank leads, which ComEd routed in to then out of the switchgear floor above. Conductive vaporized metal and combustion gases traveled along the ceiling and vented up through an open cable penetration where circuit W8020 connects to the metal clad switchgear, burning the cables cleanly off at the terminal points, and causing the feeder cable bus bars to arc to metal cabinet parts.

[80] "Cable Mockup" drawing, September 27, 2005.

Because DC control power was lost by this time the W8020 circuit breaker could not trip to clear the fault. The extensive damage to the switchgear indicated that the arcing likely continued for minutes. The extreme heat at the ceiling in the southeast corner of the cable space galled the ceiling above the fire and likely caused the metal hatch cover, located only a few feet away, to become very hot. It appears that heat radiated from the hatch to heat the center section of the battery bank, nearest the hatch, sufficiently to cause the polymer battery cell container material to ignite and spread to other cells. Acid spilled, and polymer and lead melted, vaporized, and contaminated the switchgear room. The flames, heat, and smoke from the burning battery cells damaged the DC panel, the DC isolation switch, the battery charger, the annunciator panel, and the sump pump controls.

The initial fault only damaged one feeder cable. Fire and arcing caused nine more feeder cables, one bus with three circuit breakers, and the battery to fail. The remaining nine un-faulted feeders were de-energized to allow fire fighters to extinguish the battery fire and for ComEd to commence repairs. Collateral damage and necessary repairs, including replacing damaged and failed cable and the burned battery, rerouting cables from damaged switchgear to other breakers, and the cleanup of the smoke and other conductive and hazardous materials contamination of the control room, switchgear, and cable space contributed to the delay in restoring some feeders.

### b. Analysis

The fire propagated in the extremely hot air produced by arcing of the energized cables to their grounded concentric neutrals, and to the metal cable racks. Arcing continued because the fire burned DC control cables preventing protection system operation. ComEd could have prevented the fire propagation if it had wrapped the cables surrounding the faulted joint. The only fire prevention enhancement implemented at Downers Grove was a fire detection system. The root cause was ComEd’s inadequate implementation of known fire prevention enhancements in the Downers Grove substation cable space. ComEd developed these enhancements from lessons learned from previous cable space fires. Contributing factors related to the cable space design, lack of automatic fire suppression, cable material flammability, feeder cable congestion, unsealed openings, and delayed de-energizing of the substation.

The following presents Liberty’s assessment of the direct, intermediate, and root causes, and contributing factors of the fire propagation.

*C1. A direct cause of the fire propagation was the arcing that occurred between cable conductors and concentric neutrals and metal racks and other cables.*

The cable space mock-up and photographs of the cable space taken after the fire showed extensive burning and vaporizing of the copper concentric neutrals and the steel cable racks.[81] Arcing, rather than just burning of cable materials, caused this burning. Arcing caused extremely high temperatures, as indicated by the galled cable space ceiling and the destruction of feeder cables and the control cable pan.

[81] Response to Data Request #17.

*C2. An intermediate cause of the fire propagations was the loss of DC breaker control power.*

The fault at the W805 joint started the fire. The burning cable jackets spread the fire and burned control cables and the station battery leads while feeder cables were burning. When feeder cables faulted, physical evidence indicates that they arced to their concentric neutrals and to the steel cable racks or to other cables for a considerable time. The conflagration consumed some sections of copper concentric neutrals and steel racks.[82] If the feeder breakers had had power and operated as designed, the cable arcing should have been relatively minor. Some of the DC breakers tripped and therefore, the fire damaged at least some of the breaker control cables resulting in the some loss of breaker control, which caused extended arcing in the cable space.

*C3. A direct cause of the fire propagation is ComEd's failure to wrap fire resistant tape around cables surrounding the joints on feeder W805.*

ComEd did not wrap the W805 joint and the surrounding cables with fire resistant materials. The purpose of wrapping surrounding cables is to prevent the propagation of a fire caused by a joint fault, even if the joint wrap did not contain the fire.

Wrapping of cables was included in ComEd's 1998 "Guidelines for Cable Space Improvements."[83] However, ComEd did not require retrofitting the existing feeders in cable space substations with these enhancements. If ComEd had wrapped the W805 joint and surrounding cables, collateral damage would not likely have occurred and ComEd could have prevented a lengthy, total substation outage.

ComEd reported that it has a pilot program for wrapping cables, but Downers Grove was not included.[84] ComEd reported that it found that concerns about safely wrapping energized cables and limited feeder outages prevented it from implementing a comprehensive cable-wrapping program. Liberty observed that ComEd had draped flame resistant material between cables and control cable pans in the cable spaces of other substations.[85] This would provide increased protection to control cables from cable fires, but it would not prevent the spread of fire among feeder cables.

After the fire, ComEd replaced all feeder joints and cables in the Downers Grove substation cable space with fire-retardant cables and moved control cable to the upper level. Therefore, it will not need fire wrapping at Downers Grove.

*C4. The root cause of the fire propagation was ComEd's inadequate implementation of lessons learned.*

ComEd had not applied all the fire prevention enhancements to the Downers Grove substation cable space that it learned from the 1996 Bartlett cable space fire and that it included in the 1998 "Guidelines for Cable Space Improvements." These enhancements included standards

[82] Response to Data Request #17.
[83] Response to Data Request #82.
[84] Response to Data Request #101.
[85] Bartlett on November 3, 2005, and Crestwood on October 27, 2005.

specifically on wrapping cable joints and surrounding cables with fire resistant tape and sealing floor penetrations. Smoke alarms and requiring that personnel keep cable space hatches closed were the only enhancements for reducing fire propagation that ComEd applied at Downers Grove substation.

*C5. A contributing factor related to fire propagation was ComEd's cable space design.*

ComEd built the first cable space 2-4-6[86] substation similar to Downers Grove in 1965. ComEd built about 110 of them between 1965 and 1995. ComEd designed its cable space substations to allow ComEd to increase distribution capacity substantially as load grew with minimum cost and maximum use of available land. Apparently, ComEd did not consider fire in the design of the cable spaces. ComEd routed control cables in pans just above power cables, and as ComEd added feeders to Downers Grove, feeder cables became congested.

*C6. A contributing factor related to fire propagation was the lack of an automatic fire suppression system.*

If ComEd had installed an automatic fire suppression system in the Downers Grove substation cable space, it would have reduced collateral damage and prevented a lengthy, total substation outage. ComEd would have minimized its costs and costs to customers resulting from the fire and outage. ComEd has automatic fire suppression systems in place in some of its Chicago substations.[87]

*C7. A contributing factor related to fire propagation was the flammability of the cable jacket material.*

The jackets on cables, including fire-retardant cables, have an ignition temperature of about 350° C. The material used in fire-retardant cable jackets produces low smoke and water in a fire and does not promote fire propagation.[88] ComEd has been installing fire-retardant cables in cable spaces since 1996. At least one feeder with fire-retardant cable was involved in the propagating fire. Although the jacket on this feeder's cable was charred, it did not ignite.

*C8. A contributing factor of fire propagation was congestion of power cables near the joint fault.*

The fire on the W805 cable ignited the two cables on the rack arm just above the joint. The W8002 cable had extruded cross-linked polyethylene, or XLPE, insulation. All other cables on this rack had ethylene propylene rubber, or EPR, insulation. After the materials on the W8001 and W8002 cables were set afire and faulted, the XLPE insulation melted and fed the fire. The resulting flames and arcing spread down the cables a few feet as flames and arcing burned away copper concentric neutral wires and cable material.

[86] "2-4-6" substations get their name from two 138 kV lines, four 40 MVA transformers, and six 12 kV buses.
[87] Interview September 29, 2005.
[88] Response to Data Request #102.

The standard spacing of 750 MCM cables in manholes on the 30-inch support rack arms is two sets of power cables, 10 inches apart.[89] It appears that ComEd uses a common Construction Specification for manhole cable routing specifications and cable spaces. The third rack arm carried four sets of power cables, nearly touching each other. These four sets of cables were set afire and the three energized cables faulted and arced. The intense heat, flame, and arcing then consumed a section of the control cable pan, mounted on the top rack arm.

The spare, or retired, cable on the top feeder cable support arm added more fuel to the fire. In addition, ComEd could have reduced congestion if it placed two cables on each arm. Feeder cable congestion increased the propagation of the fire.

*C9. A contributing factor related to the fire propagation was ComEd's failure to seal openings between the cable space ceiling and the switchgear.*

Air fed the fire through unsealed cable openings in the ceiling of the cable space. Sealing of cable penetrations was included in ComEd's 1998 "Guidelines for Cable Space Improvements." However, ComEd did not fully implement these enhancements at Downers Grove. The unsealed openings vented the fire likely causing it to propagate more and faster than if ComEd had sealed the openings.

*C10. A contributing factor of the fire propagation could have been ComEd's delay in de-energizing the substation.*

The tripping of breakers that cleared feeder faults and most of the damage to control cables and by extended arcing in the Bus 5 switchgear had already either occurred before or as the fire fighters arrived. However, ComEd may have prevented the destruction of the station battery if it had de-energized the substation when the fire fighters arrived about 15 minutes after the initial trip.

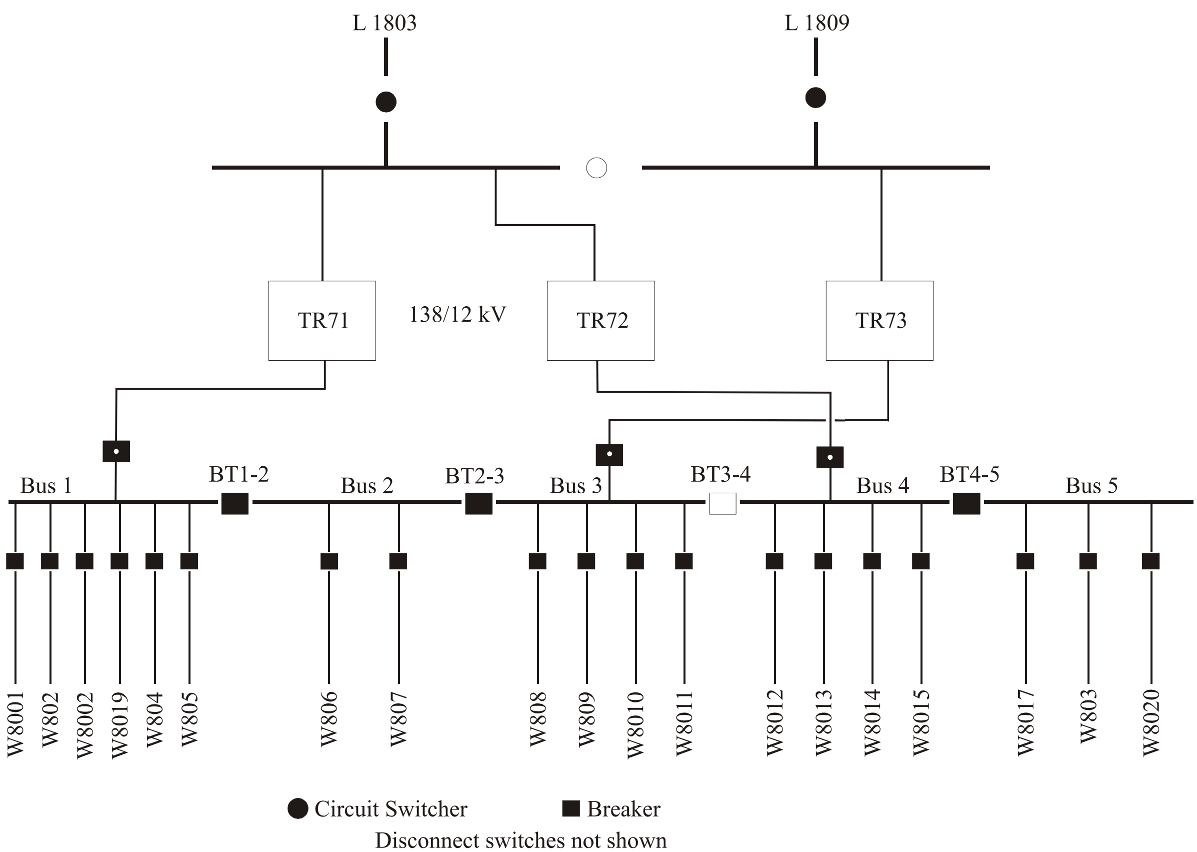
## 4. Bus 5 Switchgear Damage

### a. Background

The five 12 kV buses at the Downers Grove substation were in two bus groups.[90] One group included buses 1, 2, and 3 and fed by transformers connected to buses 1 and 3. The other bus group included buses 4 and 5 and fed by the third transformer connected to Bus 4. All bus tie breakers were closed, except for the Bus-Tie (BT) 3-4 breaker, where the design intentionally splits the two bus groups. The buses not connected to transformers had overload and differential protection that trip the tie and feeder breakers. Only differential relays protected the buses fed from transformers. Overload relays for protecting transformers also protected the transformer buses. Each feeder had time-delay over-current and reclosing over-current relays. Typically, ComEd does not use instantaneous tripping relay elements, which could reduce fault energy, in

[89] Response to Data Request #57, Standard C5048.
[90] Response to Data Request #18.

order to coordinate distribution fuses with the station circuit breakers. Feeder W805 had older style electro-mechanical, time-delay, over-current relays on Phases A and B, and the neutral. The neutral relay provided protection for phase C faults and backed up relays on the other phases for ground faults.[91] In case transitory events such as a lightning strike caused a fault, the feeders had reclosing relays that caused feeder breakers to close and re-energize feeders 2 seconds and 30 seconds after the initial trip. When a breaker tripped after reclosing twice it locked out, or stopped trying to re-energize the feeder. ComEd last tested the relays for W805 in August of 1998. After the fire, ComEd determined that the over-current relays operated properly but that the W805 reclosing relay malfunctioned. The diagram below is a simplified drawing of the Downers Grove substation.[92]




*Breaker Operations*

The following discussion is Liberty's analysis of breaker operations during the Downers Grove fire event. Because of the fire's damage, the loss of SCADA, and the failure to record completely as-found information upon first entering the substation, some breaker operations are best estimates. Photographs taken after the fire recorded some as-found information.

[91] ComEd's new style programmable relays have time over-current elements for each of the three phases, with neutral protection.
[92] Response to Data Request #18.

*Bus 1 Breaker Operation*

Bus 1 has a transformer breaker, six breakers for feeders W805, W802, W804, W8001, W8002, and W8019, and feeds Bus 2 via the normally closed bus tie BT1-2 breaker. After the fire started, all Bus 1 feeders faulted except W8019, which ComEd had routed away from the initial fault. Feeder breaker W805 tripped at 4:31 p.m. for the initial fault. The analysis of trouble call reports[93] shows that calls started coming in about 2 minutes after the initial fault. Based on this approximate two-minute delay, four feeders, W802, W804, W8001, and W8002, were all dropped at about 4:40 p.m., or about 9 minutes after the initial fault. Feeder W8019 did not de-energize until ComEd opened the 138 kV circuit switchers at Woodridge, about 57 minutes after the initial fault. The transformer breaker did not trip and the bus stayed energized. It appears that bus tie breaker BT 1-2 tripped, dropping the Bus 1 feed to Bus 2. ComEd personnel found feeder breakers W805, W8001, W8002, W802, and W804 open after the fire. They found the transformer breaker and feeder breaker W8019 closed after the fire.

At least feeders W804 and W8002 tripped from their time-delay, over-current relays because these relay targets are visible on photographs taken after the fire.[94] ComEd's investigation team indicated that the Bus 1 differential and lockout relays also operated. This action should have tripped the transformer breaker and the bus tie BT1-2 breaker, as well as the feeder breakers. Overload protection for Bus 1 includes the transformer and therefore may not be sufficiently sensitive to trip for a feeder fault.

There was no reason for the differential relay to operate because no bus fault occurred. If the differential relay did trip, it did so because either the current or trip cables were burned, or because of imbalance current transformer saturation induced by close-in fault current. Burned control cables would have had prevented the transformer breaker and feeder W8019 from tripping if the Bus 1 differential relay had tripped.

Liberty concluded that the Bus 1 feeder breakers and the transformer breaker performed as they should have for feeder faults. Possibly, the Bus 2 overload relay tripped the bus tie breaker BT1-2. However, if the Bus 1 differential relay tripped as reported, the fire would have had to damage various Bus 1 breaker control cables just before 4:40 p.m. In addition, this had to occur before the fire burned the battery leads open just before 4:41 p.m.

*Bus 2 Breaker Operation*

Bus 2 has two breakers for feeders W806 and W807, and receives feed from Bus 1 through the normally closed bus tie BT1-2 breaker and from Bus 3 through the normally closed bus tie BT2-3 breaker. The analysis of trouble call reports indicates that both feeders W806 and W807 dropped about 4:40 p.m., but not necessarily at the exact same time. ComEd personnel found both feeder breakers and both tie breakers open.[95]

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[93] Based on response to Data Request #146.
[94] Response to Data Request #17.
[95] Interview, October 13, 2005.

Liberty concluded that the Bus 2 protection did not operate as intended. Feeder W807 and BT2-3 should not have tripped. Bus 2 has overload protection as well as differential protection. It appears that the overload protection tripped the feeder and tie breakers (there is no transformer breaker in Bus 2). Either the Bus 2 overload relay did not coordinate with the relay for the faulted feeder W806, or the fire damaged at least feeder W807 and the bus tie BT2-3 control cables, before 4:40 p.m. This had to occur before the fire burned the battery leads open just before 4:41 p.m.

*Bus 3 Breaker Operation*

Bus 3 has a transformer breaker, four breakers for feeders W808, W809, W8010, and W8011, and feeds Bus 2 via the normally closed bus tie BT 2-3 breaker. ComEd can connect Bus 3, when necessary, to bus 4 via the normally open bus tie BT 3-4 breaker. The analysis of trouble call reports indicates that the Bus 3 feeders did not drop before ComEd opened the circuit switchers about 57 minutes after the initial fault. ComEd personnel found all Bus 3 feeder breakers closed.[96]

Liberty concluded that the Bus 3 breakers performed as intended; they did not trip. None of Bus 3 feeder cables faulted and there was no indication of Bus 3 differential relay targets. Therefore, there was no need for any of these breakers to trip. If the fire damaged the Bus 3 control cables, the fire had no effect on this bus. Bus tie breaker BT2-3 likely tripped from Bus 2 problems.

*Bus 4 and Bus 5 Breaker Operation*

Bus 4 has a transformer breaker, four breakers for the un-faulted feeders W8012, W8013, W8014, W8015, and feeds Bus 5 via normally closed bus tie breaker BT4-5. ComEd personnel found the transformer and all four feeders and BT4-5 closed after the fire.[97] The analysis of trouble call reports indicates that all four Bus 4 feeders. W8012, W8013, W8014, and W8015, did not drop until ComEd opened the circuit switchers about 57 minutes after the initial fault. However, Bus 5, which has three breakers for faulted feeder W8020 and un-faulted feeders W803 and W8017, receives feed from Bus 4 only through the normally closed bus tie breaker BT4-5. ComEd personnel found all three Bus 5 feeder breakers open after the fire. The analysis of trouble call reports indicates the bus 5 feeders dropped about 4:40 p.m., but not necessarily at the exact same time. ComEd personnel reported that the indicator on one of the Bus 5 breakers was in the half-open position.

One of the Bus 5 feeders faulted. All three phases of feeder W8020 cable had burned apart where they penetrated through the switchgear floor and fell to the cable space floor, clear of the switchgear. Extremely hot and conductive materials and gases from the fire drafted along the cable space ceiling to and through the open W8020 cable penetration resulting in arcing from the W8020 bus to grounded cubicle metallic parts. The bus faulted, although the fault resistance likely was high because the fault was an arcing fault and not a “bolted” fault. The open penetration to Bus 5 may have been the closest to initial fault, about 15 to 20 feet away. From a later review of PI-Historian data, ComEd determined that current on the 138 kV line that feeds

[96] Interview, October 13, 2005.
[97] Interview, October 13, 2005.

buses 4 and 5 increased, but not to a level that would have alarmed the TSO dispatcher, around 4:43 p.m., for a period that ComEd thought was over a minute. However, this observation may not be accurate. A program called PI-Historian records line load history, measured through the SCADA system, in 20 second intervals. However, because of program design, the system integrates analog data, and therefore an analyst cannot determine the exact magnitudes and time. The purposes of program do not include providing accurate data for short time events.

Liberty concluded that the Bus 4 feeder breakers operated as intended. The feeders were not faulted and the feeder breakers did not trip. However, explaining why the bus tie BT4-5 did not trip and why the two un-faulted Bus 5 feeders tripped is difficult. It is possible that the Bus 5 overload relay tripped at about 4:40 p.m., because of the "close in" feeder W8020 cable fault causing the tripping of all three Bus 5 feeder breakers. However, the fire must have damaged the tie breaker BT4-5 control cable preventing it from also tripping. Then after the DC was lost at about 4:41 p.m., the bus fault occurred and the differential relay and the tie breaker could not trip because DC had been lost by that time. Because the bus tie breaker BT4-5 would not trip, Bus 5 remained energized from Bus 4 and continued to feed the Bus 5 fault for a considerable period. The fault must have only cleared when the consumption of metal parts by the arcing caused a sufficient air gap to extinguish the arc. It appears that the fire damaged control cables for Bus 5 protection and the tie breaker before 4:40 p.m.

*Control Cables and DC Power*

ComEd personnel found the positive and negative battery leads shorted but burned apart from the load side where they ran in the cable space just above the initial fault.[98] It is likely that DC was lost just before 4:40 p.m. It is also likely that the fire damaged individual trip and DC circuits before this time.

### b. Analysis

The fire severely damaged the Bus 5 switchgear cubicles. Therefore, the three breakers on Bus 5 were not available during the restoration process. Damage to the Bus 5 switchgear could have been prevented if ComEd had sealed the W8020 cable penetration to the Bus 5 switchgear, if the DC control power had at not been lost, or if the fire had not propagated to the unsealed opening. As discussed above, some breakers did not operate because of burned control cables. However, the only major damage likely caused by this was the severely damaged Bus 5 switchgear.

The damage to Bus 5 switchgear was the result of a cable fault that did not promptly clear. This fault occurred because of the propagation of the fire and unsealed cable penetrations. The fault did not promptly clear because of the loss of DC breaker control power. The root cause is ComEd's inadequate implementation of known fire prevention enhancements in the Downers Grove substation cable space. Contributing factors include the routing of control cables and station battery leads.

[98] Response to Data Request #17.

*D1. The direct cause of the Bus 5 switchgear damage was a bus fault over an extended time.*

A fault occurred on a cable inside the Bus 5 switchgear. The bus conductor arced over to the grounded metal cubicle parts. Hot conductive gases produced by the burning and arcing of the W8020 cable likely initiated the bus fault. It is also possible that the bus could have faulted first, caused by hot contaminated air vented into the switchgear from the cable space, then the burning and faulting of the W8020 cables followed. Whatever actually happened, ComEd observed an increase in current on the 138 kV line that feeds buses 4 and 5 for a period that it thought was over a minute. Apparently arcing on Bus 5 continued until the arcing opened an air gap sufficiently large to extinguish the arc.

*D2. An intermediate cause of the Bus 5 switchgear damage was unsealed openings between the cable space ceiling and the switchgear floor.*

Unsealed cable openings in the ceiling of the cable space fed the fire. Besides a small opening through the ceiling near the battery, the opening nearest the fire was to feeder W8020 switchgear, about 15 feet from the faulted joint. This opening must have vented the fire. Flames, extremely hot gases, and vaporized metals went to the opening, causing feeder W8020 cables to burn apart, and Bus 5 to fault. Arcing on Bus 5 was unabated because by this time the DC control power had been lost. The conflagration destroyed a portion of the switchgear.

*D3. An intermediate cause of the Bus 5 switchgear damage was the loss of DC power.*

From the timeline analysis, it appears that feeder W8020 breaker tripped, but Bus 5 stayed energized because bus tie breaker BT4-5 did not trip. This indicates that the fire damaged either the station battery leads or BT4-5 control cables before the bus fault.

*D4. An intermediate cause of the Bus 5 switchgear damage was burning of DC power cables or station battery leads.*

Extensive arcing would not have occurred if the feeder circuit breakers had tripped promptly. This indicates that the fire damaged the station battery leads or relaying and breaker control cables within about 10 minutes after the fire started. Some of the DC control breakers tripped during the fire. The heat of the fire may have tripped the DC breakers. However, if they tripped because of burning of control cables, then the fire damaged the control cables before it burned the station battery leads. The result of losing DC power is important, not the actual sequence.

*D5. An intermediate cause of the Bus 5 switchgear damage was the propagation of the fire.*

If the cable space fire had not spread to Bus 5 switchgear through the open W8020 penetration and had not damaged the control and DC power cables, extended arcing on Bus 5 would not have occurred.

*D6. The root cause of the Bus 5 switchgear damage was ComEd's inadequate implementation of lessons learned.*

ComEd's failure to implement fully fire prevention enhancements resulted in the propagation of the fire, which caused both the bus fault and the burning of control cable that extended the bus fault.

*D7. A contributing factor related to the Bus 5 switchgear damage was ComEd's routing of control cable in the cable space.*

ComEd mounted a control cable pan about one foot above the burning and arcing feeder cables on the top arm of the cable rack. The flames and extremely high temperatures at that location severely burned the pan and the control cables. The extreme heat galled the ceiling above the control cable pan. ComEd did not consider relocating control cable pans to above the switchgear in cable space enhancements developed after previous fires. If it had, the placement of the control cable pans in the cable space would be a direct cause. After the fire, ComEd moved the Downer Grove control cable pans to the main floor above the switchgear.

*D8. A contributing factor related to the Bus 5 switchgear damage was ComEd's routing of the station battery leads in the cable space.*

As part of its station battery maintenance testing and maintenance procedures, on May 27, 2005, ComEd began the replacement of the Downers Grove 125V station battery.[99] The battery bank was located on the east wall near the south wall. Because ComEd replaced a three-tiered battery bank with a longer two-tiered bank, it relocated the sump pump control and the circuit breaker test cabinet.[100] ComEd rerouted the positive battery lead in and out of the cable space, just above the W805 joint, to the relocated disconnect switch. ComEd previously routed the negative lead in and out of the cable space and did not change it. The station battery leads were exposed to the extreme heat, as shown by the galling of the cable space ceiling near the leads.

The intense arcing fire beneath the battery leads shorted the positive and negative leads and burned apart the leads to the DC breaker panel. Either the burning of control cables or the loss of DC power appeared to have prevented the bus tie breaker BT4-5 from tripping for the Bus 5 switchgear fault. Had ComEd complied with its July 30, 2004, standard for routing battery cables above the cable space, ComEd may have prevented the loss of Bus 5 circuit breaker dc power.

## 5. Station Battery Fire

### a. Background

The fire and intense heat in the Downers Grove substation cable space produced a fire that destroyed the station battery on the main floor of the substation. The contamination produced by

[99] Response to Data Request #83.
[100] Response to Data Request #83.

the battery fire required environmental cleanup that delayed the start of repairs and restoration of the substation by about 12 hours.

### b. Analysis

The cause of the station battery fire was the propagation of the cable space fire. The root cause is ComEd's inadequate implementation of known fire prevention enhancements at the Downers Grove substation cable space. ComEd developed these enhancements from lessons learned from previous cable space fires. Contributing factors include the un-insulated access hatch and ComEd's delay in de-energizing the substation.

*E1. The direct cause of the station battery fire was the propagation of the cable space fire.*

Heat from the fire in the cable space radiated the steel access hatch to ignite the polymer battery cell cases. The fire destroyed much of the station battery.[101]

Heat from the flames and arcing in cable space below and a few feet from the station battery, was so intense that it galled the cable space ceiling. When the fire fighters entered the control building they found that the cable space fire had self-extinguished. However, the station battery fire was on fire and the burning cells were exploding, emitting toxic gases and particles. Fire fighters extinguished the fire about one hour and twenty-one minutes after the initial fault.[102] The destruction of the station battery did not contribute to the cable space fire and did not cause the loss of DC power. DC control power was lost earlier when the fire burned the control cables and battery leads.

*E2. A root cause of the station battery fire was ComEd's inadequate implementation of lessons learned.*

As analyzed in section above on fire propagation, ComEd's failure to implement fully fire prevention enhancements resulted in the propagation of the fire, which caused the station battery fire.

*E3. A contributing factor related to the station battery fire was ComEd's placement of the station battery over the cable space near a metal cable space access hatch.*

The Downers Grove's station battery was just above the cable space fire and near a steel cable space access hatch. If ComEd had located the station battery at some other location, it may not have burned. ComEd did not build the Downers Grove substation control building with a separate station battery room, as done by some other utilities, isolated from the cable space and

[101] Response to Data Request #17.
[102] Response to Data Request #128.

the switchgear. If ComEd had placed the station battery in a different location, the cable space fire may not have affected the battery.

*E4. A contributing factor related to the station battery fire was the un-insulated steel hatch.*

ComEd's policy is to keep the hatches to the cable space closed when people are not in the cable space and to stencil this requirement on or near the access hatches. At Downers Grove, it appeared that personnel had closed the hatch before the fire occurred. It also appeared that the hatch likely radiated most of the heat that ignited the station battery.[103] Possibly, ComEd may have prevented the station battery fire if it insulated the steel cable space access hatch with a flame resistant material or if it was not located close to the battery.

*E5. An intermediate cause of the station battery fire was ComEd's delayed de-energizing of the substation.*

Had ComEd de-energized the Downers Grove substation in a timely matter, the battery may not have caught on fire.

## 6. Time to De-Energize Substation

### a. Background

Fire fighters need to have a substation de-energized before they attempt to extinguish a fire. In addition, arcing of energized parts adds energy to a fire and can cause a fire to propagate. In general, substation damage will be less and restoration faster if the operations personnel de-energize the substation as soon as possible after the start of a fire.

If operations personnel had de-energized the Downers Grove substation in a timely fashion, ComEd could have avoided some of the damage and consequences of the fire. There were sufficient indications available to the operations personnel that the appropriate course of action was to de-energize the substation long before they finally took that action. Even when operators decided to take that action, there were additional delays.

If operations personnel had taken decisive actions, they may have prevented the destruction of the station battery. Even if operators delayed some but still took the necessary actions, ComEd could have avoided some of the damage. By the time the substation was finally de-energized and fire fighters entered the building, the cable space fire had self-extinguished and all they had to do was spray a small amount of foam to extinguish the station battery fire.

Fire fighters responded very quickly to the fire. They were immediately aware of a ComEd problem because they had received a fire alarm trouble call from a retail store caused by the power outage, noticed that the fire house power had been lost, received a call at about 4:45 p.m. from 911 that smoke was coming from the substation, and almost simultaneously saw the smoke.

[103] Response to Data Request #17.

The fire station is located right next to the substation. They arrived about a minute later, or about 15 minutes after the initial trip, cut the lock and chain on the gate, opened a control building door, and saw that smoke filled the control room. They also reported hearing banging noises, which could have been breakers tripping. The fire fighters called the ComEd 800 number and reported the fire.[104] The ComEd customer service representative logged the call as a "fire department standby," which is not as urgent and does not require immediate attention as does a "structure fire."[105] This appeared as a lower urgency to the Operations Dispatcher. The fire fighters would not commence fire fighting until the substation was de-energized.

The OCC[106] Load Dispatcher received two alarms at 4:31 p.m. The first alarm was the "lock out"[107] of feeder W805 breaker.[108] A Downers Grove control building fire alarm followed the W805 alarm by nine seconds. A feeder change-of-status is a priority 1 alarm on the alarm screen. The fire alarm is priority 2. The Load Dispatcher reported that he did not see the fire alarm because it scrolled off the screen when "bus rocking" alarms come in.[109] Bus rocking is multiple feeder voltage alarms caused by feeder faults. However, the list of these alarms as indicated on the screen was only a few inches long and the multiple feeder faults did not occur for several minutes after SCADA was lost.[110]

At 4:38 p.m., the Load Dispatcher[111] ordered an Area Operator to the Downers Grove substation to investigate the lock out. At 4:39 p.m., the Load Dispatcher lost SCADA indications from the Downers Grove substation, and the TSO[112] Dispatcher received a loss of channel alarm. By 4:33 p.m., the OCC Operations Dispatcher[113] started receiving W805 trouble calls and ordered an OES (trouble man) to investigate the W805 outage at 4:41 p.m. By 4:43 p.m., the OCC started receiving trouble calls for feeders on Bus 1, Bus 2, and Bus 5. By 4:45 p.m., the Load and Operations dispatchers realized that more than a single feeder breaker had tripped. The Load Dispatcher told the Area Operator who was on-route that a bus had been dropped. The Operations Dispatcher started to order more OES and crews to the Downers Grove substation. The Area Operator in route to TDC580 reported that traffic was slowing his progress because traffic signals were out. He arrived at 5:05 p.m. and reported to the Load Dispatcher that the substation was on fire. However, the Area Operator did not explain that the fire was inside the control building. At 5:05 p.m., Area Operator requested and received permission from the Load Dispatcher to de-energize the Downers Grove substation.[114] The OES, who also happened to be firefighter, donned breathing apparatus, and, with a fire fighter, entered the smoke-filled control building to open circuit breakers. Because the OES was not familiar with substation controls, the

[104] Interview, November 3, 2005.
[105] Response to Data Request #195.
[106] OCC is the Operations Control Center.
[107] ComEd called this a lock out, but the breaker had just tripped. The reclose relay malfunctioned.
[108] The breaker did not actually lock out. It tripped and did not recluse.
[109] Interview, September 28, 2005.
[110] Response to Data Request #64.
[111] The load dispatcher at the OCC controls all equipment in the substation via SCADA or an area operator.
[112] TSO is the Transmission System Operations via trouble men (called OES).
[113] The operations dispatcher at the OCC controls all feeder equipment outside the substation.
[114] The OCC did not need TSO permission to drop TDC580.

Area Operator gave instructions from the doorway. Because the DC power had been lost, the OES could not make any of the breakers trip.[115]

At 5:17 p.m., the OCC Load Dispatcher told the TSO that the on-site Area Operator had no local control and to "dump the substation if possible" from the circuit switchers at Woodridge. At 5:21 p.m., the TSO called the OCC and asked if the 12 kV transformer breakers were open. The Load Dispatcher told the TSO that the Area Operator could not confirm the breaker position. At 5:23 p.m., there was more discussion between the OCC and the TSO. At 5:24 p.m., the Area Operator discussed the situation with the OCC and the TSO. The OCC Shift Manager ordered the TSO to "dump it now." At 5:27 p.m., the OCC called the TSO and requested that they open the circuit switchers. Nothing happened until an OCC Shift Manager ordered that the TSO open the circuit switchers. By 5:29 p.m., the TSO opened both circuit switchers at Woodridge and the incoming 138 kV lines to Downers Grove were finally de-energized. About 12 minutes of discussion and debate occurred between the time the Area Operator reported that he had no local control and the de-energizing of the substation. Some of the issues discussed and misunderstandings occurring during this period included:[116]

- what part of the substation was on fire
- why the substation could not be dumped locally
- who had control of circuit switchers at Downers Grove and at Woodridge
- what equipment personnel could operate manually at Downers Grove.

### b. Analysis

The Load Dispatcher was slow to respond to the initial breaker lockout, and was not aware of the fire until the Area Operator arrived even though there was an SCADA fire alarm, a call from the fire department, trouble calls from multiple feeders, and loss of SCADA. ComEd had not provided the OCC and TSO any guidelines about when to drop a substation for a fire, the fire fighters had no direct communications with the OCC, and no hazard communication documents were on site. The language used by the Area Operator, the Load Dispatcher, and the TSO dispatcher was often not clear, accurate, and formal, causing confusion and inaction. In addition, the OCC did not know who controlled the circuit switchers and neither the OCC Dispatcher nor the TSO knew that the circuit switchers could be hand cranked to interrupt load or fault current.

*F1. A direct cause of ComEd's delay to drop the substation was the slow response by the OCC to dispatch an operator.*

ComEd's OCC did not dispatch an Area Operator until about 7 minutes after the initial breaker trip alarm. Much of fire damage in the cable space likely occurred before the OCC dispatched an Area Operator.

[115] Responses to Data Requests nos. 64, 128, 178, 155, 66, 22, 149, and 186.
[116] Response to Data Request #66.

*F2. A direct cause of ComEd's delay to drop the substation was that the OCC did not know about the fire until the Area Operator arrived.*

ComEd's Load Dispatcher did not notice the fire alarm that displayed 9 seconds after the breaker lockout alarm. He claimed that the alarms scrolled off the screen.

*F3. An intermediate cause of ComEd's delay to drop the substation was the priority ComEd gave to substation fire alarms.*

Feeder breaker lockouts have a priority 1 on ComEd's alarm display screen. Substation fire alarms have a priority 2 and not accompanied by any kind of special audio alarm. The alarm program allows the dispatcher to filter on multiple priorities, including fire alarms.[117]

*F4. A contributing factor related to ComEd's delay to drop the substation was that neither the fire department nor a security service monitors fire alarms.*

A security service monitors fire alarms in substations in Chicago. When an alarm occurs, the service calls both the fire department and ComEd.[118] The Downers Grove substation is not in Chicago.

*F5. An intermediate cause of ComEd's delay to drop the substation was that ComEd did not notice the fire fighters call.*

The fire department dispatch center called ComEd's 800 number to notify it of the fire and to obtain an estimated time of arrival. A ComEd customer service representative received the call and did not assign the call as the highest level of emergency.[119] The OCC apparently did not notice the fire trouble call.

*F6. An intermediate cause of ComEd's delay to drop the substation was ComEd's failure to notice that the accumulated inputs indicated a cable space fire.*

There was sufficient information coming into ComEd's OCC to identify that there was a fire in the Downers Grove control building and that there was more than a feeder lockout. First, there was the combination of the breaker lockout and the fire alarm. Second, SCADA was lost. Third, there were trouble calls on one feeder and then multiple feeders. Fourth, there was the fire department trouble call. Long after these indications were available, dispatchers discussed the possibility of a "dig-in" causing the problem at some place remote from the substation. ComEd's OCC dispatchers were inattentive and did not assess the particular combination of indications available to them.

[117] Response to Data Request #156.
[118] Interview, September 29, 2005.
[119] Response to Data Request #158.

*F7. A contributing factor related to ComEd's delay dropping the substation was that ComEd has no method or system to verify a fire alarm before an operator arrives.*

In order to have dropped the substation, it is reasonable to have some analytical method or back up system to verify fire alarms. However, ComEd reports that it has some false fire alarm trouble alarms, but few false fire alarms. The question is which is more risky, the chance of dropping a substation in error, or the lengthy outage caused by the collateral damage from the fire.

*F8. A direct cause of ComEd's delay to drop the substation was that ComEd had no clear instruction to determine when to drop a substation.*

It appeared that ComEd had not provided its OCC and TSO Dispatchers instructions regarding when to drop a substation when it is on fire. Moreover, there appeared to be a reluctance to drop the substation even after ComEd finally made the decision to do so.

*F9. A direct cause of ComEd's delay to drop the substation was that there was no direct communication between the fire fighters and ComEd's OCC before the Area Operator arrived.*

The fire department did not have a direct line of communication with the OCC until ComEd's Area Operator arrived at the substation.

*F10. A direct cause of ComEd's delay to drop the substation was the lack of easily accessible documents for fire fighters at the substation.*

There were no MSDS hazardous material documents, warnings, instructions for notifying ComEd, and basic layout drawings in an easily accessible place in the substation for firefighters and first responders.

*F11. A direct cause of ComEd's delay to drop the substation was that ComEd's Area Operator, OCC, and TSO did not communicate in a clear and definitive manner.*

ComEd's Area Operator, OCC, and TSO did not use concise, firm, and formal language to describe the fire and the need to drop the substation, at least until an OCC Shift Manager made a formal order to open the circuit switchers.

*F12. A direct cause of ComEd's delay to drop the substation was that ComEd's operation personnel had inadequate knowledge at the OCC of whether the OCC or the TSO control the circuit switchers.*

Part of the discussion between ComEd's OCC and TSO was about who controlled the circuit switchers at Downers Grove.

*F13. A direct cause of ComEd's delay to drop the substation was that ComEd's operation personnel had inadequate knowledge of equipment capability.*

ComEd's Area Operators did not know that the circuit switchers at Downers Grove could interrupt load or fault current by opening by the hand crank. ComEd could have saved at least 10 minutes if the OCC had told its operator to open manually the circuit switchers.

*F14. A root cause of ComEd's delay to drop the substation was that ComEd did not have a comprehensive fire plan for Downers Grove substation.*

ComEd would have reduced delays if it had provided formal and easily accessible general instructions to its OCC personnel for actions to take for cable space fires.

*F15. A root cause of ComEd's delay to drop the substation was ComEd's inadequate operations training of operations personnel for cable space fires.*

ComEd would have reduced delays if it had trained its Area Operators, Load Dispatchers, Operations Dispatchers, and first responders for cable space fires, followed by drills involving fire departments.

## 7. Lengthy Restoration Time

### a. Background

*Substation Restoration*

The substation restoration process started when ComEd sent text messages to its emergency response personnel at 4:45 p.m. Other than the operations personnel, the first ComEd representative on site was the substation maintenance engineering (AME) manager. He obtained information for the fire fighters and communicated with the OCC. The Site Restoration Management (SRM) team members and the Emergency Operations Center (EOC) team members received text messages and traveled to either the substation or the OCC. The Engineering Vice President arrived at about 6:00 p.m. and assisted with media communications. The first SRM team member also arrived at about 6:00 p.m. to take over communications with the OCC; the rest of the team arrived within a couple of hours to start gathering information for the EOC. The EOC team assembled at the OCC and began taking charge of both the restoration of the substation and the feeders.[120]

Because of a minor re-strike of the fire, fire fighters did not allow ComEd full access to the control building until 9:38 p.m. ComEd's hazardous material expert found that hazardous lead and acid had contaminated the building and restricted access to it. A contractor cleaned up the

[120] Responses to Data Requests #66 and #128.

hazardous contamination and ComEd crews could start work inside the control building about 12 hours after the fire started.[121]

The fire destroyed the station battery, many of the power and control cables, portions of the Bus 5 switchgear, and miscellaneous equipment. Smoke had contaminated controls, relays, and insulation throughout the control building. ComEd determined that it could restore Bus 3 first, and it concentrated on disassembling equipment for cleaning and testing, including Bus 3, relays, and controls. ComEd tested the transformers, replaced necessary power cables, and installed new control cables above the switchgear. The substation and underground crews had Bus 3 energized 32 hours after starting work.

*Feeder Restoration*[122]

Because of hazardous contamination caused by the station battery fire, the repair of the substation did not begin until about 12 hours after the fire. However, transferring loads to other substations, via ties to external feeders, began immediately. ComEd restored power to about 903 customers about two hours after the initial fault. By the end of the first 12-hour period, ComEd transferred to other substations the loads on seven feeders and substantial portions of five feeders, all of which had external ties. In addition, ComEd installed two 2 MW generators to restore power to critical customers. In all, ComEd restored power to about 9,981 customers, or 46 percent of all customers served by the Downers Grove substation, during the first 12 hours.

During the second 12-hour period, ComEd restored power to about 2,795 more customers by transferring remaining loads on four of the feeders with external ties, by installing a 2 MW generator to pick up load on a portion of a feeder without external ties, and by installing two 2 MW and one 500 kW generators to restore power to three critical customers. Progress in restoring power during the second 12-hour period slowed because the switching to provide sufficient transfer capacity was more complex, and because of the substantial time required to move, place, and connect generators.

During the first 24-hour period, ComEd restored power to about 12,776 customers, or about 59 percent of the customers served by the Downers Grove substation. Based on ComEd's capacity planning studies, the system has the capacity to pick up about 55 percent of the Downers Grove total design summer peak load during the first 24 hours of switching.[123] Although the percentage of customers restored is not the exactly the same as the percentage of load transferred, this level of restoration appears to be in line with the system capacity studies.

During the third 12-hour period, ComEd restored power to an additional 2,064 customers. ComEd transferred loads on one of the feeders without external ties, and on the remaining portion of one feeder with external ties to other substations. ComEd installed two 500 kW generators to restore power to critical customers, and connected one 2 MW generator to increase the capacity of one transferred feeder.

[121] TDC 580 Downers Grove Fire Root Cause Investigation, RA01.01
[122] Responses to numerous data requests and Liberty analyses.
[123] Response to Data Request #215.

ComEd restored power to the last 6,671 customers, or 31 percent of all Downers Grove substation customers, about 44 hours after the outage began. Five feeders that did not have external ties served these customers. ComEd restored power to these feeders by energizing Bus 3 at Downers Grove.

*Feeder Restoration Time Line*

| **Date/Time** | **Feeder / Event** | **# Customers Affected** |
|---|---|---|
| August 10 | | |
| 4:31 p.m. | Feeder W805 joint fault | 1,458 |
| 4:40 p.m. | Approximate time feeders tripped automatically | 10,186 |
| 5:28 p.m. | Remaining feeders dropped by opening circuit switchers | 9,868 |
| | Total customer losing electric service because of fire | 21,512 |
| | Customers restored during the first 12 hours | |
| 6:40 p.m. | W8002 – 40 percent restored via J925 from DCJ92, Lemont | 903 |
| 7:00 p.m. | W8015 – restored via W3625 from TSS136, Burr Ridge & W386 from DCW38, Downers Grove Twp | 609 |
| 7:15 p.m. | W8017 – restored via W031 & W039 from TSS103, Lisle | 1230 |
| 7:50 p.m. | W8001 – restored via W595 from TDC 559, Woodridge | 1028 |
| 8:25 p.m. | W8014 – restored via W6122 and W617 TDC561, Bolingbrook | 1139 |
| 9:05 p.m. | W806 – 75 percent restored via W3607 from TSS136, Burr Ridge | 710 |
| 9:30 p.m. | W8019 – restored via W6125 from TDC561, Bolingbrook | 69 |
| 11:50 p.m. | W8011 – 75 percent restored via W036 from TSS103, Lisle | 921 |
| 11:58 p.m. | W805 - Restored via W3613, TSS136, Burr Ridge & W640, DCW640, Tri-State Village | 1458 |
| August 11 | | |
| 1:00 a.m. | W8020 – 50 percent restored via J295 from DCJ92, Lemont | 30 |
| 1:11 a.m. | W8011 – remaining 25 percent restored via W591, TDC559, Woodridge | 307 |
| 1:30 a.m. | W8012 – 50 percent restored via W4572 from TSS145, York Center | 988 |
| 2:00 a.m. | W8020 – restored [redacted] via 2 MW generator | |
| 2:20 a.m. | W807 – 66 percent restored via W387, DCW38, Downers Grove Twp | 589 |
| 4:45 a.m. | restored Fairview Apartments via 2MW generator | |
| | Total customers restored first 12 hours | 9981 |
| | Customers restored during the second 12 hours | |
| 7:00 a.m. | W8013 – restored [redacted] via 2 MW generator | |
| 10:45 a.m. | W8013 – restored [redacted] via 2 MW generator | |
| 11:20 a.m. | W802* – 25 percent restored via 2 MW generator | 400 |
| 12:40 p.m. | W806 – restored remaining 25 percent via W3607, TSS136, Burr Ridge | 236 |
| 2:53 p.m. | W807 – restored remaining 34 percent via W387, DCW38, DG Twp | 303 |
| 2:55 p.m. | W8012 – restored remaining 50 percent via W419, SS558, Westmont | 988 |
| 3:58 p.m. | W8013* – restored via W3625 from TSS136, Burr Ridge | 840 |
| 3:58 p.m. | W808* – restored [redacted] via a 500 kW generator | |
| 4:20 p.m. | W8020 – restored additional 49 percent (all but 1 percent) | |

| | | |
|---|---|---|
| | via WJ925, DCJ92, Lemont | 28 |
| | Total customers restored second 12 hours | 2795 |
| | | |
| | Customers restored during the third 12 hours | |
| 7:15 p.m. | W803* – 50 percent restored via W595 from TDC559, Woodridge | 354 |
| 7:15 p.m. | W804* – restored [redacted] via 500 kW generator | |
| 8:27 p.m. | W8002 – remaining 60 percent restored via W3625, TSS136, Burr Ridge | 1356 |
| 10:45 p.m. | restored Darien Police Department via 500 kW generator | |
| August 12 | | |
| 4:30 a.m. | W803* – remaining 50 percent restored via W595, DC 559, Woodridge | 354 |
| 4:45 a.m. | W803* – Installed a 2 MW generator to assist W803 | |
| | Total customers restored third 12 hours | 2064 |
| | | |
| | Customers restored between hour 36 and hour 44 | |
| 8:42 a.m. | W8020 – final 1 percent restored via W3625 from TSS136, Burr Ridge | 1 |
| 12:35 p.m. | Bus 3 energized | |
| 1:00 p.m. | W808* – restored via Bus 3 | 1341 |
| 1:29 p.m. | W802* – remaining 75 percent restored via W808 | 1198 |
| 1:36 p.m. | W809* – restored via Bus 3 | 1412 |
| 1:36 p.m. | W804* – restored via W809 | 1466 |
| 1:45 p.m. | W8010* – restored via Bus 3 | 1254 |
| | Total customers restored between hour 36 and hour 44 | 6672 |
| | Total customers restored | 21,512 |

*** indicates feeder with no external ties**

### b. Analysis

*Substation Restoration*

The extensive damage that occurred to the substation feeder and control cables, the station battery, and the switchgear, and the necessary clean up and repair work prevented using the substation equipment at Downers Grove from picking up any load for 44 hours. As discussed in previous sections, if ComEd had completed known fire prevention enhancements, the extensive equipment damage causing the lengthy substation outage would not have occurred. Although first responders could have been better prepared, once the emergency management leadership took over, the clean up and repair work started timely and continued around the clock until after ComEd re-energized Buses 3 and 4. Considering the contamination and the extent of the damage, the substation restoration process was appropriate.

*Feeder Restoration*

ComEd started feeder restoration promptly, and transferred most of the loads on the twelve feeders with external ties within 12 hours. Because seven of the feeders could not be tied to feeders from other substations, and because the system could only pick up about half of the Downers Grove loads within 24 hours, finding excess capacity on the system, and performing switching to use that capacity, was complex and time consuming. ComEd could not transfer the last five feeders before it restored the Downers Grove substation Bus 3, 44 hours after the outage started. It is unknown how long it would have taken to restore power to these five feeders if parts of the Downers Grove substation could not have been re-energized. However, considering the system capacity limitations, not having predetermined restoration procedures for a total and extended Downers Grove substation outage, the actions of the emergency operations center team was appropriate.

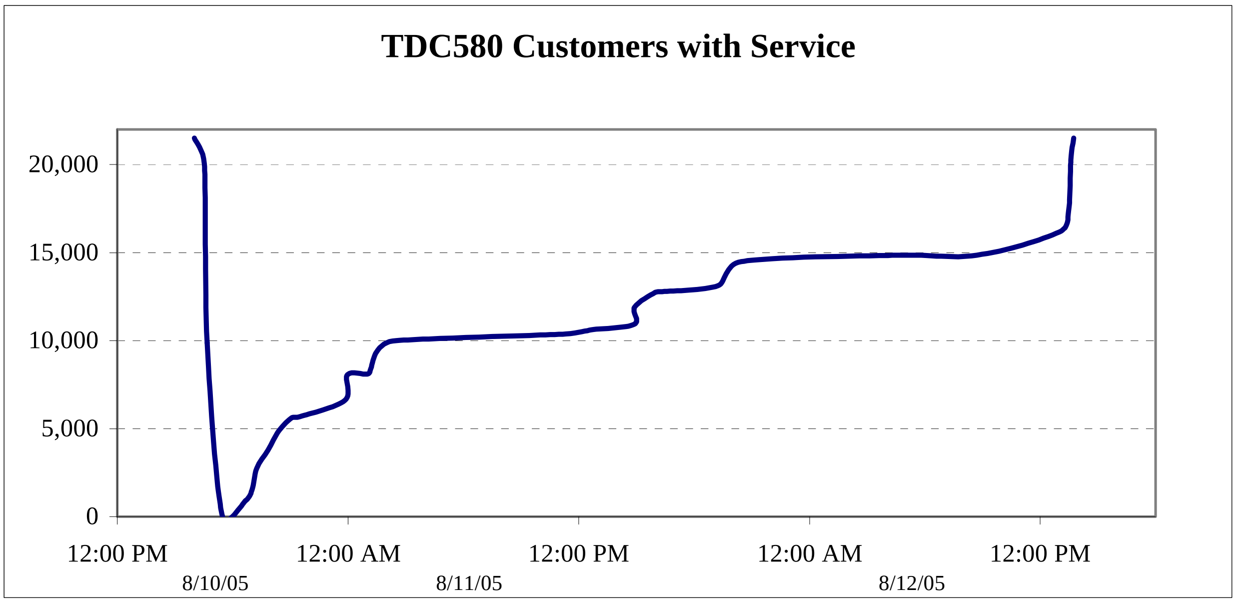
ComEd installed nine generators during the outage to facilitate restoration. Installation of generators is something not commonly done by most utilities. It used seven generators to restore critical customers and one to support a transferred feeder. It used only one to pick up stranded load on a feeder section. ComEd could have installed more generators, but it would have required about 20 more 2 MW generators to pick up the five feeders, assuming that was possible. Generator size is limited to 2 MW because of transportation limitations. ComEd also uses some 500 kW generators for smaller critical customers. Picking up stranded load with a generator requires that load on a feeder section match the generator, and that personnel can connect a generator at the proper location. Installing generators is important for restoring critical customers, but would not be a very practical means, unless ComEd planned and prepared connection points in advance, to restore power to numerous feeders at numerous locations. Three more 2 MW rental generators were readily available, and more could have been located. It is likely that these, and more, generators would have been used if Bus 3 had not been re-energized. However, the restoration time would have been very lengthy. ComEd reported that it did not have prepared high voltage leads for its rental generators. Making up high voltage leads may have delayed the installation of the rental generators. ComEd reported that it is planning to have made up leads, in various lengths, available for emergencies. During the outage, ComEd considered installing a 34/12 kV transformer to pick up load on one feeder. However, ComEd could not accomplish this for safety reasons.

Liberty's assessment of the direct, intermediate, and root causes of, and the factors contributing to, the lengthy restoration focused particularly on the inability to restore a significant number of customers for more than 24 hours.

The direct causes of the lengthy outages of some feeders were ComEd's inability to transfer all Downers Grove loads to other substations, not pre-planning switching guidelines for the total substation outage, and not pre-planning and preparing how portable generators, transformers, and switchgear were to be used to maximize feeder restorations after the total substation outage. The intermediate causes were ComEd's lack of external tie switches on five of the feeders and insufficient transfer capacity available for the Downers Grove substation total outage. A factor that did not cause, but contributed to, the lengthy outage was ComEd's failure to provide the SPOC, the SRM teams, and the EOC teams with training, guidelines, and documents needed to start more effectively the repair and restoration of the substation. The root cause of the lengthy outage for some customers was ComEd's failure to plan for total substation outages.

*G1. A direct cause of the lengthy outages of some feeders was ComEd's inability to transfer all Downers Grove loads to other substations.*

ComEd first restored the feeders that it could easily transfer. During the first 12 hours, ComEd restored about 46 percent of the customers by transfers using external ties. During the second 12 hours, restoration slowed because transfers to other substations were either difficult, or not possible. By 24 hours, ComEd had restored only 59 percent of the Downers Grove customers. During the third 12-hour period, ComEd transferred only one additional feeder and part of another. After 36 hours, ComEd had restored 69 percent of the customers. No additional feeder transfers occurred. ComEd restored the remaining 31 percent after about 44 hours, and only because it re-energized Bus 3 at Downers Grove. The diagram below shows customer restoration over time.




*G2. An intermediate cause of the lengthy restoration time was ComEd's lack of external tie switches on five of the feeders.*

ComEd planners require that each feeder have at least two ties to other feeders, located to use emergency capacity of other feeders. However, these other feeders may be internal, or from other buses of the same substation, as were 7 of the 19 feeders at Downers Grove. During the restoration, ComEd accomplished transfers of loads from most of the feeders with external ties in a reasonable time. It eventually accomplished transfers of loads of two of the feeders without external ties through complex and time consuming switching. However, it did not transfer five of the feeders without external ties to other feeders. ComEd restored them only after it restored a bus at the substation. Feeder designers connect tie switches in feeders to external feeders if such a feeder is nearby. In some cases, it may be expensive or not practical to build tie lines between feeders from different substations.

*G3. An intermediate cause of the lengthy restoration time was ComEd's insufficient transfer capacity available for the Downers Grove substation total outage.*

ComEd's capacity planning criteria requires that each substation have sufficient transfer capacity for an outage of the largest transformer, but not total substation outages. Therefore, ComEd did not purposely build its system to the transfer capacity necessary to restore power to all customers within 24 hours following a total substation outage. The design transfer capacity (in 24 hours) for a single transformer substation, not set up for connection to a portable substation, is 100 percent because ComEd cannot pick up the load from within the substation. However, because other transformers in a multiple transformer substation can share load from an out of service transformer, the minimum transfer capacity required for multiple transformer substations is 10 percent. The actual summer peak-load day transfer capacities range from 10 percent to over 100 percent, with an average of about 50 percent for all substations. Downers Grove's current summer peak-load transfer capacity is about 55 percent. If ComEd built the system so that it had a 100 percent transfer capability for the total outage of the Downers Grove substation, the resulting restoration time should have been less than 24 hours.[124] ComEd reported that building the system to provide for 100 percent transfer capacity is not practical and would be very expensive.

*G4. A direct cause of the lengthy restoration time was ComEd's failure to pre-plan switching guidelines for the total substation outage.*

ComEd completed switching feeders with external ties in a reasonable time. However, when identifying excess capacity and switching to reach that capacity became difficult, restoration slowed. Some of the factors involved with excess capacity constantly change. However, if ComEd had studied, before the outage, which feeders would likely need complex switching after a total substation outage, and had pre-determined what was likely necessary to restore these feeders, ComEd could have reduced restoration times.

*G5. A direct cause of the lengthy restoration time was ComEd's failure to pre-plan and prepare for using portable generators, transformers, and switchgear to maximize feeder restorations.*

Because the system design prevented the transfer of some feeders to other substations, ComEd needed other methods of supplying power to prevent a lengthy restoration time. ComEd has a supply of portable generators originally intended for restoring critical customers and assisting feeders. ComEd did not intend generators to be a major solution to restoring multiple feeders resulting from a total substation outage. ComEd also has portable transformers to replace temporarily substation transformers. ComEd does not have portable switchgear that might have been able to restore some of the feeders from the substation.

During this outage, ComEd installed seven generators to restore critical customers and two to restore partially power to feeder loads. The effectiveness of restoring power quickly to the five

[124] This is according to ComEd. Actual results show that it took almost 24 hours to accomplish the switching operations associated with just over half the total capacity.

feeders was limited without pre-planning and preparation. Even if the supply of generators was unlimited, at least twenty 2 MW generators would have been required to pick up the loads on the five feeders that were not transferred. Stranded loads must match generator size. This requires particular placement and connection of generators on feeders. These locations may not be accessible. In addition, it takes about 6-10 hours to install a 2 MW generator.

- The ComEd-owned generators were ready to go. However, the rental generators did not have high voltage leads. Some time was required to cut cable and install terminations on high voltage leads. This resulted in longer installation times for some generators, and may have prevented the use of the three generators not used.
- ComEd based its supply of ComEd-owned and rented on-hand generators on historical usage and not on what it would need for a total substation outage.
- ComEd had not planned how it could best use, place, and connect portable generators, transformers, or switchgear to restore a larger portion of the feeders without external ties. ComEd considered using a 34/12 kV portable transformer to pick up the load on a feeder. However, the proposed site was not suitable; the installation would have been unsafe.

*G6. A contributing factor related to the long restoration time was ComEd's failure to provide the SPOC, the SRM teams, and the EOC teams with training, guidelines, and documents needed to prevent delays in starting the repair and restoration of the substation.*

The process ComEd followed to start the repair of the substation was generally good. The broadcast paging for a SPOC, for the SRM team members, and the EOC team members was effective. Once ComEd started the repair process, except for some safety related delays, it worked around the clock to repair the substation equipment. However, the following were factors that had some affect on starting the substation repair and restoration process.

- The first non-operations responder, ComEd's SPOC, did not have guidelines or a checklist regarding exactly his role.
- ComEd's SRM team did not have easy access to important and up-to-date drawings, and it did not have a hazardous materials list and guide. Waiting for the hazardous materials person delayed slightly their initial progress. The SRM teams were not required to maintain comprehensive records.
- ComEd's SRM teams, the EOC teams, and substation operations personnel did not have guidelines, and had not practiced actions to follow for the restoration of a total substation outage caused by fire.

*C7. The root cause of the lengthy outage was ComEd's failure to plan for a total outage of the Downers Grove substation.*

A combination of ComEd's system design and ComEd's failure to pre-determine how it could restore all Downers Grove loads within 24 hours caused the lengthy restoration. ComEd had not studied the effect of an extended outage of the Downers Grove substation, had not planned, and documented what design changes it must make, or restoration actions prepared, to prevent lengthy customer outages in preparation for a total substation outage.

# III. Substations Similar to Downers Grove

This chapter provides the results of Liberty's assessment of whether other substations in ComEd's power delivery system could fail in a way similar to the TDC580 failure.

## A. Background

### 1. Description of Similar Substations

Any substation in which solid dielectric power cables route through a cable space has the potential of a fire similar to the one that occurred at Downers Grove. However, there are more than 75 "2-4-6"[125] substations similar to Downer's Grove that have the highest risk of cable space fire. These substations include Schaumburg, Bartlett, and Pleasant Hill, all of which experienced cable space fires. ComEd has implemented fire protection enhancements to some of these substations to reduce the risk. There are additional multi-transformer substations with cable spaces that also have various degrees of risk of a Downers Grove-like fire depending on factors such as cable congestion and implemented fire prevention enhancements.

Cable space substations are those that have sub-grade areas, or cable spaces, located under indoor switchgear, where power cables route from the switchgear to the outside. In some of these substations, ComEd has also routed control cables in the cable space. The power cables in the cable spaces may be lead covered cables, PILC[126], or solid dielectric cables, XLPE[127] or EPR[128], or a combination of the lead and solid dielectric. Several other large utilities use cable space substations.[129]

Fires in ComEd's cable spaces all occurred in 2-4-6 substations built similar to Downers Grove. Fire propagated from a joint or cable fault to other cables because of their close proximity to the initial fault. ComEd designed its 2-4-6 cable space substations with a capacity of up to four 40 MVA transformers, six buses, and about 30 feeders, and with control cables in the cable spaces.[130] In general, those substations with three or four transformers have more congested cable spaces, depending on how ComEd routed cables within a particular substation. ComEd did not have a cable routing standard during the 1963-1995 period when it built these substations. After the Bartlett fire, ComEd designed the 2-4-6 substation at Lake Zurich without a cable space. Since that time, ComEd built new substations without cable spaces.

The physical size of the substation limits the capacity of conventional substations with outdoor overhead distribution switchgear. To minimize the number of substations needed to provide future capacity, in the early 1960s, ComEd began building substations using the new solid dielectric cables and compact indoor switchgear. ComEd used the new solid dielectric cables to connect switchgear to the transformers and the feeders. ComEd designed these substations for

125 "2-4-6" substations get their name from two 138 kV lines, four 40 MVA transformers, and six 12 kV buses.
126 PILC is paper insulated, lead covered cable.
127 XLPE is cross-linked polyethylene.
128 EPR is ethylene propylene rubber.
129 Response to Data Request #210.
130 At Downers Grove Substation, the control cables were moved to above the switchgear after the fire.

growth. The advantage of a cable space is to provide access for pulling cable and to reposition cables to balance loads as substation capacity and number of feeders increase.

ComEd has not reached the full capacity on some of these substations. In 1996, about one-half of the 2-4-6 cable space substations had only two transformers.[131] As capacity is increases, so too will the number of feeder cables in the cable space. Unless ComEd implements fire prevention enhancements, the risk of a Downers Grove fire will increase as ComEd routes more cables through a cable space.

ComEd's other multi-transformer, cable-space substations have non-typical designs and may have more or less design capacity than the 2-4-6 indoor substations. Although cable space fires have not occurred in any non-typical cable space substations, the risk of fire exists.

Cable spaces contain only distribution power and control cables, never transmission cables. However, ComEd located transmission cables at the Fisk and Taylor substations in tunnels that have similarities to cable spaces because fires in either space can affect other circuits.[132]

ComEd has not built any cable space substations since the Bartlett fire in 1996. ComEd routes power cables in its new "Concept" substations in underground concrete encased conduits to breaker terminals accessible only from the exterior of the switchgear buildings.

### 2. Identification of Similar Substations

ComEd made efforts to identify cable space substations with a fire risk in 1996 and in 2005, and in other years. In 1996, after the Bartlett cable space fire, ComEd identified 87 cable space substations with indoor switchgear and solid dielectric cables, 43 with 3 or 4 transformers, and 44 with 2 transformers.[133]

In 2005, after the Downers Grove fire, ComEd identified similar substations on the basis of new criteria; substations have cable spaces, 12 kV indoor switchgear, and the potential of a large number of solid dielectric cables.[134] Initially, ComEd identified 110 substations thought to fit these criteria.[135] This list included 86 of the 87 substations on the 1996 list, plus 24 additional substations. After inspecting the 110 substations, ComEd found that seven did not have cable spaces.[136] A table in the next section of this report identifies the 103 cable space substations having characteristics similar to Downers Grove as defined by ComEd.

ComEd has performed four surveys of its cable space substations aimed at identifying risk factors. In 1997, ComEd surveyed 44 substations.[137] This survey of 44 cable spaces found 411 sets of cable joints, many open floor penetrations, and five with fire detection systems.[138]

[131] Response to Data Request #57.
[132] Response to Data Request #9.
[133] Responses to Data Requests #57 and #118.
[134] Response to Data Request #16.
[135] Response to Data Require #16.
[136] Response to Data Requests #16, addendum, and #118.
[137] Response to Data Request #222.

In 2005, ComEd surveyed 103 cable space substations and found 757 sets of joints, 41 cases where station battery leads were in the cable space, complete floor penetration sealing in only 2 substations, and 23 cable spaces that did not have fire detection systems.[139] However, ComEd's survey did not identify how many of these joints were on solid dielectric XLPE and EPR cables.

### 3. Programs to Reduce Fire Risk

ComEd has experienced 36 substation fires over that last ten years.[140] Most of these involved either switchgear and miscellaneous other substation equipment (20) or transformers (12). Eight of the 40 fires involved cable or transmission lines.[141] While most of these fires were relatively minor events, several were significant. There have been four significant fires in the cable spaces of ComEd's substations since 1993, including Pleasant Hill in 1993, Bartlett in 1996, Schaumburg in 2001, and Downers Grove in 2005. All of these cable space substations have the typical indoor 2-4-6 design, all fires started by either a cable or joint fault, and all had a large number of solid dielectric cables with at least some cable joints.

Chapter II of this report discusses ComEd's follow-up to the fires at Pleasant Hill, Bartlett, and Schaumburg in some detail. In summary, after the Pleasant Hill fire, ComEd recognized issues related to solid dielectric cables, cable congestion, control cables routed in the cable space, and not having instantaneous relaying. ComEd indicated that it planned to seal all open cable penetrations with other work when in any cable space substation.

After the Bartlett fire, ComEd identified issues related to sealing open penetrations, joints in cable bends, no standard for routing cables, and reclosing on faults.[142] ComEd reported that in 1998, it created and funded a "Cable Space Replacement Program" for five substations.[143] By the end of 1999, ComEd replaced 37 cables in three substations. By the end of 2000, ComEd had replaced 12 additional cables.

In 2002, ComEd expanded the Cable Space Replacement program into the "Cable Space Pilot Program." It called for different cable testing methods.[144] ComEd tested 287 and replaced 53 cable sections between 1998 and 2005 at 19 cable space substations. Although Downers Grove substation was on the list of cable space substations considered, ComEd did not test at Downers Grove before the fire. From 1998 to 2004, ComEd spent almost $7.5 million on the testing and replacement of cable space cables. The peak year for this work was 1999, when ComEd spent $4.8 million.[145]

[138] Response to Data Request #222.
[139] Response to Data Request #118.
[140] Response to Data Request #171.
[141] Response to Data Request #171.
[142] Response to Data Request #57.
[143] Response to DR 104.
[144] Response to Data Request #59.
[145] Response to Data Request #59.

After the Schaumburg fire, ComEd planned to complete fire protection enhancements at the Schaumburg substation as indicated in its 1998 guide, implement a program of fire protection improvements in TSS and TDC substations, and to require personnel to call the fire department whenever there is smoke or fire in a substation.[146]

On December 6, 2005, ComEd informed Liberty about several accomplishments and initiatives related to fire protection. ComEd established a new fire protection department that includes a new manager, four employees, and a former employee brought back as a contractor.[147]

The department created a 10-year fire protection strategy that has components including fire detection systems, cable space improvements, fire seals, battery cables, site fire plans, and tunnel systems. Additional accomplishments and initiatives include:

- Engineering specification that allows sealing of floor penetrations while equipment is still energized
- Began engineering design to move substation battery mains from the cable space to the switchgear floor
- Identified 15 substations to have fire detection installed in 2006
- Evaluating fire wrapping and seals
- Engineering for the Fisk tunnel modifications
- Considerations being given to TDC substations include:
    a. Automatic and manual suppression system
    b. Updated fire detection panel
    c. Penetration fire seals
    d. Cable fire wrapping
- Develop site fire plans for substations
- Developed a substation fire-protection database.

An additional activity sponsored by the fire detection department is infrared scanning of cable space joints. As of December 5, 2005, ComEd had identified nine potential problems. Some of these showed workmanship problems on the connector.

## B. Analysis

### 1. Liberty Inspections

Liberty inspected the eight cable-space substations listed below.

1. [redacted], typical 2-4-6 substation

[146] Response to Data Request #92.
[147] Interview, December 6, 2005, and response to Data Request #225.

Liberty observed cable congestion, a large hole in ceiling of the cable space, no fire barriers for power or control cables, and a battery lead in the cable space.

2. [redacted], typical 2-4-6 substation

Liberty found no unique problems. There were flame resistant barriers for control cables.

3. [redacted], non-typical 2-transformer substation

Liberty found that ComEd had installed a new joint, counter to ComEd's guidelines. Later, ComEd reported that it removed this joint. Liberty found battery leads routed in cable space.

4. [redacted], typical 2-4-6 substation

Liberty found flame resistant barriers for control cables, openings sealed, no cable congestion, and a mold problem.

5. [redacted], typical 2-4-6 substation

Liberty found no fire barriers, sealed openings, and no cable congestion.

6. [redacted], non-typical PILC/Solid Dielectric cable space substation

This substation has both solid dielectric and PILC cable; ComEd included it on the list of similar substations. Liberty found some openings not sealed.

7. [redacted], non-typical PILC/Solid Dielectric cable space substation

Liberty found that this substation had both solid dielectric cable and PILC cable and that ComEd should consider it a cable space substation with fire risk similar to Downers Grove. It had unsealed penetrations, battery leads in the cable space, no fire resistance barriers, and control cables in the cable space.

8. [redacted], all PILC, not similar in fire risk to Downers Grove

Liberty agreed that this substation should not be on the list of Downers Grove similar substations.

ComEd's survey and Liberty's inspections indicate that although ComEd has completed some fire protection enhancements, there were many exceptions. ComEd needs to wrap or remove many joints.

## 2. Analysis of Similar Substations

The table below lists ComEd's substations similar to Downers Grove.[148] It also lists some characteristics key either to the likelihood of a similar event or to the consequences of a total substation outage. Customer counts include those also those served by other substations fed by these substations.

| Station # | Station Name | Basement Cable Joint Count | Fire Detection | Customers Served | % of Peak Transferable |
|---|---|---|---|---|---|
| [redacted] | [redacted] | 14 | Y | 13,946 | 42 |
| [redacted] | [redacted] | 10 | Y | 11,132 | 85 |
| [redacted] | [redacted] | 6 | N | 10,575 | 50 |
| [redacted] | [redacted] | 10 | Y | 15,511 | 38 |
| [redacted] | [redacted] | 23 | Y | 26,824 | 44 |
| [redacted] | [redacted] | 4 | Y | 6,324 | 124 |
| [redacted] | [redacted] | 3 | Y | 19,451 | 94 |
| [redacted] | [redacted] | 0 | Y | 5,292 | 146 |
| [redacted] | [redacted] | 0 | Y | 13,330 | 70 |
| [redacted] | [redacted] | 0 | Y | 12,791 | 35 |
| [redacted] | [redacted] | 0 | Y | 7,673 | 53 |
| [redacted] | [redacted] | 8 | Y | 21,961 | 39 |
| [redacted] | [redacted] | 2 | Y | 8,296 | 85 |
| [redacted] | [redacted] | 2 | N | 4,056 | 114 |
| [redacted] | [redacted] | 32 | Y | 10,880 | 80 |
| [redacted] | [redacted] | 0 | N | 8,851 | 59 |
| [redacted] | [redacted] | 21 | Y | 29,551 | 41 |
| [redacted] | [redacted] | 4 | Y | 8,252 | 48 |
| [redacted] | [redacted] | 5 | Y | 16,927 | 37 |
| [redacted] | [redacted] | 1 | N | 7,956 | 33 |
| [redacted] | [redacted] | 2 | N | 5,669 | 17 |

[148] Responses to Data Requests nos. 118, 215, and 224.

| Station # | Station Name | Basement Cable Joint Count | Fire Detection | Customers Served | % of Peak Transferable |
|---|---|---|---|---|---|
| [redacted] | [redacted] | 0 | Y | 4,504 | 41 |
| [redacted] | [redacted] | 3 | N | 13,256 | 50 |
| [redacted] | [redacted] | 0 | Y | 8,480 | 66 |
| [redacted] | [redacted] | 1 | N | 4,356 | 55 |
| [redacted] | [redacted] | 0 | Y | 9,503 | 81 |
| [redacted] | [redacted] | 0 | Y | 14,485 | 46 |
| [redacted] | [redacted] | 6 | Y | 27,593 | 28 |
| [redacted] | [redacted] | 3 | Y | 20,967 | 47 |
| [redacted] | [redacted] | 1 | Y | 30,569 | 38 |
| [redacted] | [redacted] | 0 | N | 8,938 | 61 |
| [redacted] | [redacted] | 0 | Y | 3,162 | 103 |
| [redacted] | [redacted] | 0 | N | 7,857 | 47 |
| [redacted] | [redacted] | 0 | Y | 10,614 | 38 |
| [redacted] | [redacted] | 2 | N | 4,814 | 72 |
| [redacted] | [redacted] | 1 | N | 12,348 | 61 |
| [redacted] | [redacted] | 2 | Y | 29,384 | 36 |
| [redacted] | [redacted] | 0 | Y | 19,981 | 37 |
| [redacted] | [redacted] | 0 | N | 12,960 | 30 |
| [redacted] | [redacted] | 1 | N | 10,596 | 35 |
| [redacted] | [redacted] | 0 | N | 9,686 | 57 |
| [redacted] | [redacted] | 18 | Y | 23,330 | 36 |
| [redacted] | [redacted] | 9 | Y | 9,724 | 128 |
| [redacted] | [redacted] | 12 | Y | 12,289 | 74 |
| [redacted] | [redacted] | 4 | N | 8,591 | 86 |
| [redacted] | [redacted] | 2 | Y | 15,821 | 43 |
| [redacted] | [redacted] | 3 | N | 5,295 | 54 |
| [redacted] | [redacted] | 6 | Y | 24,552 | 29 |
| [redacted] | [redacted] | 8 | Y | 21,571 | 34 |
| [redacted] | [redacted] | 2 | N | 7,788 | 94 |
| [redacted] | [redacted] | 32 | Y | 11,667 | 30 |
| [redacted] | [redacted] | 1 | N | 5,437 | 97 |
| [redacted] | [redacted] | 5 | Y | 6,600 | 57 |

| Station # | Station Name | Basement Cable Joint Count | Fire Detection | Customers Served | % of Peak Transferable |
|---|---|---|---|---|---|
| [redacted] | [redacted] | 3 | Y | 23,117 | 39 |
| [redacted] | [redacted] | 2 | Y | 7,393 | 68 |
| [redacted] | [redacted] | 0 | Y | 25,207 | 53 |
| [redacted] | [redacted] | 9 | Y | 24,110 | 28 |
| [redacted] | [redacted] | 8 | Y | 5,633 | 82 |
| [redacted] | [redacted] | 19 | Y | 22,995 | 59 |
| [redacted] | [redacted] | 7 | Y | 24,689 | 45 |
| [redacted] | [redacted] | 6 | Y | 13,822 | 49 |
| [redacted] | [redacted] | 15 | Y | 11,555 | 39 |
| [redacted] | [redacted] | 11 | Y | 13,927 | 33 |
| [redacted] | [redacted] | 9 | Y | 21,067 | 107 |
| [redacted] | [redacted] | 13 | Y | 31,414 | 20 |
| [redacted] | [redacted] | 0 | Y | 26,891 | 55 |
| [redacted] | [redacted] | 0 | N | 19,879 | 24 |
| [redacted] | [redacted] | 4 | Y | 8,264 | 19 |
| [redacted] | [redacted] | 3 | Y | 20,449 | 42 |
| [redacted] | [redacted] | 5 | Y | 8,521 | 106 |
| [redacted] | [redacted] | 13 | Y | 23,408 | 25 |
| [redacted] | [redacted] | 3 | N | 8,362 | 52 |
| [redacted] | [redacted] | 20 | Y | 20,412 | 43 |
| [redacted] | [redacted] | 8 | N | 10,562 | 11 |
| [redacted] | [redacted] | 18 | Y | 27,502 | 45 |
| [redacted] | [redacted] | 4 | N | 9,520 | 22 |
| [redacted] | [redacted] | 5 | N | 12,748 | 45 |
| [redacted] | [redacted] | 0 | Y | 12,064 | 69 |
| [redacted] | [redacted] | 1 | Y | 18,722 | 53 |
| [redacted] | [redacted] | 5 | N | 7,539 | 66 |
| [redacted] | [redacted] | 6 | Y | 14,524 | 100 |
| [redacted] | [redacted] | 4 | Y | 27,747 | 38 |
| [redacted] | [redacted] | 9 | Y | 27,650 | 54 |
| [redacted] | [redacted] | 2 | Y | 22,957 | 21 |
| [redacted] | [redacted] | 19 | Y | 8,438 | 64 |

| Station # | Station Name | Basement Cable Joint Count | Fire Detection | Customers Served | % of Peak Transferable |
|---|---|---|---|---|---|
| [redacted] | [redacted] | 22 | Y | 25,552 | 41 |
| [redacted] | [redacted] | 22 | Y | 30,315 | 24 |
| [redacted] | [redacted] | 17 | Y | 23,516 | 23 |
| [redacted] | [redacted] | 14 | Y | 16,451 | 52 |
| [redacted] | [redacted] | 26 | Y | 51,293 | 19 |
| [redacted] | [redacted] | 0 | Y | 16,739 | 46 |
| [redacted] | [redacted] | 11 | Y | 12,383 | 57 |
| [redacted] | [redacted] | 17 | Y | 23,731 | 37 |
| [redacted] | [redacted] | 0 | Y | 18,306 | 70 |
| [redacted] | [redacted] | 12 | Y | 17,481 | 37 |
| [redacted] | [redacted] | 10 | Y | 4,849 | 31 |
| [redacted] | [redacted] | 17 | Y | 28,184 | 22 |
| [redacted] | [redacted] | 31 | Y | 32,394 | 32 |
| [redacted] | [redacted] | 2 | Y | 37,014 | 32 |
| [redacted] | [redacted] | 27 | Y | 68,177 | 17 |
| [redacted] | [redacted] | 13 | Y | 43,934 | 20 |
| [redacted] | [redacted] | 16 | Y | 29,625 | 36 |

Of course, there are more data available on these substations. However, even this list shows that there are many cable space joints and a large number of substations without any fire detection system. These joint counts include both pre-molded joints on solid dielectric cables and joints on PILC lead covered cables. However, most of the cable space substations listed contains only pre-molded joints. ComEd has a method for estimating the number of pre-molded joints in those substations that contain both types.[149]

A fire in the cable space of a substation can cause an extended total substation outage. Joint faults on solid dielectric cables have been the major cause of past cable space fires. Therefore, one simplified way of determining the likelihood of a cable space fire is by identifying the number of joints on solid dielectric cables in the cable space. Similarly, a simplified way of measuring the consequences of such an outage is by identifying the number of customers that ComEd would not be able to transfer to other substations (or stranded) within 24 hours during peak load conditions. Multiplying the number of joints times the number of stranded customers (in 1000 units) provides a ranking that ComEd could use to help understand its vulnerabilities and prioritize its work efforts.

[149] Interview, December 15, 2005.

For example, the [redacted] substation has 20 cable joints and could strand about 11,600 customers [(1 – 0.43) x 20,400]. [redacted]'s ranking factor is 20 x 11.6= 232. In comparison, the [redacted] substation has 17 cable joints and could strand about 22,000 customers [(1 - 0.22) x 28,000]. [redacted]'s ranking factor is 17 x 22 = 374, and would have a higher initial priority for fire prevention enhancements than would [redacted]. The ranking factor could be illustrated better for determining where to the apply fire prevention enhancements for the greatest effect if the substations were plotted by decreasing ranking factor. To use the above table for this analysis, ComEd will need to eliminate those joints on non-dielectric (lead) cables.

ComEd's initial strategy includes prioritizing fire enhancement efforts on a combination of fire risk and consequences of stranding customers.[150]

Other relevant factors include whether joints have been infrared inspected, whether floor penetrations are sealed, whether the substation has a fire detection system, and whether station battery leads route through the cable space. The next chapter of this report describes a method of making a more detailed assessment.

[150] Interview, December 15, 2005.

# IV. Assessment of All Substations

## A. Introduction

### 1. Background

In addition to investigating the specific matters related to the Downers Grove fire incident and evaluating substations similar to Downers Grove, the ICC requested that Liberty determine to what extent ComEd's system is vulnerable to other widespread electric service interruptions due to insufficient switching capacity or other means to restore service when an entire substation is lost. Stated another way, the ICC wanted to know whether ComEd's power delivery system is such that a total substation loss, regardless of the cause of the loss, would cause sustained or widespread service interruptions.

NERC, through its ten Regional Reliability Councils, is responsible for ensuring the reliability of the nation's electric infrastructure. The ComEd system belongs to the Mid America Interconnected Network Incorporated (MAIN) Reliability Council. These organizations do not specify that the electrical power system be required to withstand the loss of an entire substation without loss of load. However, their criteria do require that utilities analyze low probability events that could have severe consequences. These so-called extreme contingencies include events such as the loss of an entire generating station and the loss of all lines on a right-of-way among others. The purpose of these analyses is to understand the power system response under extreme outage conditions including the effects of the event on adjoining power systems and to develop mitigation plans to prevent propagation of those effects. The purpose of these analyses is not to determine whether a particular subset of customers will be subject to an extended service interruption, but to show that the interconnected transmission network has a high likelihood of withstanding the event. Moreover, the loss of a substation is not one of the conditions that NERC/MAIN specifically requires that utilities design the system for without loss of load.

Complete substation outages do occur and good utility practice suggests looking at them with a perspective of its effect on customers, not simply the survival of the power system. ComEd estimated that over the last ten years it had at least 34 incidents of complete substation outages.[151] The Downers Grove fires, as well as the other, similar fires discussed in the above sections of this report, were complete substation outages. An aspect of these incidents that distinguishes them from a catastrophic loss of substation event is the degree to which a utility could use equipment at the substation to restore service in a reasonably short period. As described in Chapter II above, ComEd restored customers' service after the Downers Grove fire by switching some load to other substations, by using mobile generating equipment, and by re-energizing circuits within the Downers Grove facility itself. After the Pleasant Hill fire, ComEd had the capability to transfer 100 percent of the load to other substations. However, that fire occurred in 1993 during winter loading conditions. Today, ComEd estimates that it could only transfer 59 percent of the Pleasant Hill load during peak summer conditions.[152]

[151] Response to Data Request #22.
[152] Response to Data Request #27.

This task examines the planning and consideration that ComEd has given to a situation in which there is a total substation loss and the extent of the substation damage is such that service cannot be restored using the affected substation for a considerable length of time. This is not a task that examines an event so low in its likelihood of occurrence that it is unreasonable to consider. The consequences of the Downers Grove fire could easily have been worse. Other actual incidents of the loss of a substation on the ComEd system could also have been more severe in terms of the damage to substation equipment. In addition, natural causes such as severe weather (e.g., tornadoes) or human-caused events (e.g., airplane crash, terrorist activity) could destroy a substation to the extent that all or very little of its facilities would be usable for restoration. For example, a well-publicized natural event occurred in the California earthquake of 1971, destroying a Los Angeles Department of Water and Power major DC conversion substation and severed its DC link to the Pacific Northwest. The collapse of the World Trade Center towers on September 11, 2001, completely destroyed two major Consolidated Edison substations.

Good utility practice is at least to have considered the likelihood and effect (both in terms of customers affected and duration) of catastrophic substation failures and to have evaluated the measures that it would have to take to reduce that effect to some acceptable level. Only with a full understanding of a catastrophic event can a utility make reasonable decisions with regard to which situations require action and whether any cost effective actions should target either the likelihood or the effect of such an event.

### 2. ComEd's Substations

The ComEd power system is comprised of approximately 800 substations that perform a variety of functions. To a substantial degree, each substation is unique in the details of its design and service. However, there are ways to describe generally ComEd's substations. Its identification number points to the function of each substation. The following paragraphs describe each of the six general functions served by ComEd substations.[153]

ComEd identified traditional Generating Stations as STAXX.[154] There are 16 such substations on the ComEd system. Substations at the six nuclear plants and ten fossil plants serve to connect generation to the transmission system. These facilities also perform switching operations on the transmission system that reconfigures the bulk power path. Some STAXX substations include transformers to supply distribution load at 34 kV, 12 kV, or 4 kV; one of these substations directly serves over 50,000 customers.[155]

ComEd identifies newer Independent Power Producer Stations as TSS9XX. There are 15 such substations on the ComEd system. Similar to the traditional generating stations, these substations connect generation from independently owned generating sources to the transmission system. Some of these substations have the capability to perform switching operations on the transmission system that reconfigures the bulk power path and others that do not have such

[153] Response to Data Request #216.
[154] Where the "XX" or "XXX" in the designation is a unique number.
[155] Response to Data Request #224.

capability tap directly onto transmission lines. None of these substations includes transformers that serve customers other than themselves.

ComEd identifies Transmission Substations as TSSXXX. There are 132 such substations on the ComEd system. These substations perform switching operations on the transmission system that reconfigures the bulk power path. Some of these substations interconnect to other transmission voltage levels (765 kV, 345 kV, 138 kV, and 69 kV) using transformers. Some TSSXXX substations include transformers to supply distribution load at 34 kV, 12 kV, and 4 kV, directly serving from as few as 35 customers to as many as over 85,000 customers.[156] In addition, some TSSXXX substations presently operate as Transmission Distribution Centers (TDCs), but have the capability to perform transmission-switching operations.

ComEd identifies Transmission Distribution Center Substations as TDCXXX. There are 106 such substations on the ComEd system. These substations transform transmission voltage levels (138 kV, and 69 kV) to distribution voltage levels (34 kV, 12 kV, or 4 kV). Typically, ComEd does not use these substations to perform switching operations on the transmission system; however, ties do exist between transmission lines. These substations are typically either an ultimate two transmission lines/two transformers/two 12 kV distribution bus design (2-2-2) or an ultimate two transmission lines/four transformers/six 12 kV distribution bus design (2-4-6). TDC substations on ComEd's system directly serve as few as about 1,000 customers to as many as nearly 30,000 customers.[157] A few TDCXXX substations also contain transformers to supply distribution load at 34 kV. Downers Grove is a TDC substation, TDC580.

ComEd identifies "Substations" as SSXXX. There are 48 such substations on the ComEd system. These substations perform switching operations on the 34 kV sub-transmission system in the suburbs and the 12 kV system in Chicago. Typically, these substations include transformers to supply distribution load at 12 kV or 4 kV. SSXXX substations directly serve up to nearly 13,000 customers.[158]

ComEd identifies Distribution Center substations as DCXXX. There are 482 such substations on the ComEd system. DCXXX substations transform sub-transmission voltage levels (34 kV) to distribution voltage levels (12 kV or 4 kV). Other DCXXX substations transform 12 kV distribution voltage to 4 kV distribution voltage and are typically in Chicago. DCXXX substations serve a wide range of number of customers up to over 7,500 customers.[159]

[156] Response to Data Request #224.
[157] Response to Data Request #224.
[158] Response to Data Request #224.
[159] Response to Data Request #224.

## B. Analysis

### 1. ComEd's Experience

ComEd identified 34 events in the last ten years in which power from an entire substation was lost for greater than 5 minutes.[160] There may have been more such events because ComEd does not formally track such events. However, it is unlikely that there have been any significant events that ComEd did not identify. The following tables generally describe these 34 events in terms of number of customers affected, total duration, and causes.

**10 Year Summary of Total Substation Loss Events – Causes and Impacts**

| Number of Events | Number of Customers Affected |
|---|---|
| 2 | < 5,000 |
| 10 | 5,000 – 10,000 |
| 12 | 10,000 – 20,000 |
| 10 | >20,000 |

| Number of Events | Duration |
|---|---|
| 10 | < 1 hour |
| 9 | 1 hour – 4 hours |
| 5 | 4 hours – 8 hours |
| 8 | 8 hours – 24 hours |
| 2 | > 24 hours |

| Number of Events | Event |
|---|---|
| 9 | Fire |
| 8 | Equipment Failure |
| 3 | Natural Cause |
| 3 | Loss of Source |
| 2 | Animals |
| 9 | Human |

In addition to the Downers Grove incident, the other event that resulted in the loss of electric service to customers for more than 24 hours was a July 1999 failure at the Northwest substation that caused a loss of source power to six other substations that obtain their source feed(s) only from the Northwest substation. This incident affected over 43,000 customers and is exactly the type of event that ComEd could identify and analyze to determine if cost effective risk reduction or impact mitigation is practical or economic. Another example is the October 2000 outage of the Jefferson substation. Although the outage only lasted approximately 6 hours and affected fewer customers (26,000), those customers were located in the heart of downtown Chicago. Going back

[160] Response to Data Request #22.

more than 10 years, there was a fire at the Crawford substation in 1990 that affected customers for three full days.[161]

The limited ten-year historical information suggests that while a total loss of a substation is a reasonably likely event, events that had consequences lasting more than 24 hours are less frequent. However, and for example, it does not stretch the imagination to see how the Downers Grove incident could have had more significant consequences. ComEd estimated that it could transfer 55 percent of the peak load on the Downers Grove substation to other substations.[162] The August 10, 2005, fire occurred on a high load day, but not on a design peak load day. This allowed ComEd to transfer more load to other substations. The fire did not damage Bus #3 at Downers Grove. This enabled ComEd to re-energize Bus #3 and restore service to a significant number of customers for which ComEd had no other immediate alternatives for the restoration of electric service. Finally, the fire did not damage any of the three substation transformers and associated outdoor equipment. Such damage could have complicated service restoration and lengthened customer interruptions.

## 2. Benchmarking

An industry association conducted a survey regarding aspects of distribution capacity planning.[163] ComEd and 23 other utilities responded to the survey, which asked questions regarding loss of load for a distribution transformer failure, the ability to pick up load from adjacent circuits, and planning for an outage of two transformers. The majority of the respondents including ComEd allowed loss of load in some instances for the loss of a single distribution substation transformer. The majority of the respondents including ComEd had some capability for adjacent circuits to pick up load for a circuit outage. A minority of the respondents including ComEd consider the loss of two distribution substation transformers under special circumstances.

While this survey was not directly on point for the topics addressed in this report, it showed that aspects of ComEd's distribution capacity planning were in line with the practices of other U.S. utilities.

Liberty attempted to acquire information on total substation outages for ComEd and other utilities but it was not available. However, ComEd supplied information regarding the contribution of substation performance to the 2004 System Average Interruption Frequency Index (SAIFI) for a group of over 20 companies including ComEd.[164] The results of that survey indicated that ComEd's 0.10 contribution from substation reliability problems to overall SAIFI for 2004 was in line with the other companies. ComEd's overall system SAIFI for 2004 was in the range of 1.16 to 1.21;[165] the contribution of substation performance to overall system

[161] Pleasant Hill Investigation Report.
[162] Response to Data Request #27.
[163] Response to Data Request #12.
[164] Response to Data Request #217.
[165] ComEd 2004 Annual reliability Report to the ICC.

interruption frequency is small. Again, while these data are not directly on point here, they do show that ComEd's overall substation performance is in line with other utilities.

### 3. ComEd's Studies

ComEd performs power system simulations in which it models the total loss of major generating and transmission substations.[166] ComEd performs these studies to test the vulnerability of its backbone transmission system to unstable conditions. ComEd's Transmission Planning Criteria requires that severe but credible contingencies should not result in cascading outages or other system instability.[167] Such analyses are also required by the MAIN reliability council's Transmission Planning Principals and Guides and the Simulation Testing of the MAIN Bulk Power Transmission System to Assess Adequacy and Reliability.[168] The purpose of the studies is not to assess the effect of the substation outage in terms of number and duration of customer interruptions, but to determine the system response to such an event, including the effects of the event on adjoining power systems and to develop mitigation plans to prevent propagation of those effects.

The results of these studies are confidential because they point out specific system vulnerabilities. However, ComEd permitted Liberty to review the results.[169] The following are general observations resulting from these studies:

Of the 9 total generating station losses simulated:

- 2 resulted in no problems (in terms of system stability)
- 5 resulted in loading and/or voltage problems at 80 percent of peak load or higher that would result in local load curtailment or the need for action to control voltage[170]
- 2 resulted in severe overloads and or voltage problems at 80 percent of peak load or higher.

Of the 24 total major transmission substation losses simulated:

- 14 resulted in no problems (in terms of system stability)
- 5 resulted in loading and/or voltage problems at loads at 80 percent of peak load or higher that would result in local load curtailment or the need for action to control voltage
- 5 resulted in severe overloads and or voltage problems at 80 percent of peak load or higher.

ComEd performed these extreme disturbance studies for locations that it believed to have the worst outcomes, with the expectation that the majority of other sites would result in less severe consequences. While it is a good thing that ComEd performs these studies and, hopefully, knows

[166] Response to data Request #26.
[167] Response to data Request #33, page 10.
[168] Response to Data Request #34, page 6.
[169] Response to Data request #204.
[170] Load curtailment is operator-initiated or automatic action that preserves the overall power system integrity by the disconnection of customers.

what actions would be required to prevent overall system problems, the studies do not help with the problem of considering the direct impact of such an event on customers.[171]

### 4. ComEd's Preparedness for Substation Problems

ComEd has a formal procedure for establishing local incident command. The procedure details the process ComEd uses when a local gas, electric, or other emergency occurs and that may require establishing on-site command and control. It also deals with coordinating the incident response, safety, and dealing with the media.[172] A Site Restoration Management Manual augments and supports this procedure. It defines the responsibilities and duties of the Site Restoration management team. [173] ComEd's restoration procedures are general in nature and designed to provide guidance for a wide variety of events.

ComEd performs monthly load shed drills conducted by PJM,[174] as well as MAIN System Restoration Drills, Main Emergency Response Drills, ComEd Emergency Preparedness Drills, and MISO[175] System Restoration Drills. These drills and the simulated events generally involve system-wide conditions and a widespread loss of load by system events or local loss of load by actions of system operators.[176] The focus of these drills appears to be on the security of the power system and not the duration of outages to customers for the complete catastrophic loss of a substation. ComEd includes the loss of an entire TDC or TSS substation in its overall system restoration procedure training.[177] Again, this focus is on an overall load restoration and not on the outages caused by catastrophic loss of a substation and the ensuing duration of customer interruptions. ComEd's liability risk committee has not evaluated or analyzed vulnerabilities to the power system.[178]

ComEd does not perform vulnerability drills or pre-planning analysis for the catastrophic loss of an entire substation.

### 5. Load Transfer Capabilities

If a total substation loss occurs, a utility has three basic ways of restoring service. It can switch loads to other substations, it can supply the loads from temporary, mobile equipment such as generators and transformers, and it can use whatever facilities are undamaged at the subject substation.

[171] ComEd informed Liberty on 12/15/05 that it had conducted additional studies to determine the effects on load and switching requirements. Liberty did not review or verify these analyses.
[172] Response to Data Request #20.
[173] Response to Data Request #96.
[174] Pennsylvania, New Jersey Maryland system operator.
[175] Midwest Independent System Operator.
[176] Response to Data Request #193.
[177] Response to Data request #194.
[178] Response to Data request #24.

With regard to transferring loads to other substations, ComEd does not plan for and does not have the capability to transfer 100 percent of most substations' loads. In its Distribution Capacity Planning Guidelines, ComEd considers substation transformer ratings. These guidelines call for the ability to transfer 10 percent of the design peak substation load for multi-transformer substations supplied at 69 kV or higher in the event of a single transformer failure.[179] The basis for this requirement is that a transformer's short-term rating is generally 10 percent higher than its long-term rating.[180]

Liberty investigated the capability of ComEd's high voltage substations to transfer load to other substations. These substations include 12 kV substations that are supplied by 69 kV or higher voltage. ComEd provided information regarding 182 such substations.[181] This group of substations does not include transmission and generating substations that do not carry load, independent power producer substations, and the almost 500 distribution center substations. The 182 substations are comprised of 3 STAXX, 77 TSSXXX, and 102 TDCXXX substations. The following table is a summary of that information as it relates to the capability to transfer load at expected 2005 peak load conditions.

**Substation Load Transfer Capability at 2005 Peak Load Conditions**

| 2005 Peak Load Transfer Capability In Percent | Number of Substations in range | | 2005 Peak Load Transfer Capability In Percent | Number of Substations in total |
|---|---|---|---|---|
| > 0 but < 10 | 2 | | > 0 | 182 |
| > 10 but < 20 | 15 | | >10 | 180 |
| > 20 but < 30 | 20 | | >20 | 165 |
| > 30 but < 40 | 33 | | >30 | 145 |
| > 40 but < 50 | 26 | | >40 | 112 |
| > 50 but < 60 | 22 | | >50 | 86 |
| > 60 but < 70 | 19 | | >60 | 64 |
| > 70 but < 80 | 15 | | >70 | 45 |
| > 80 but < 90 | 10 | | >80 | 30 |
| > 90 but <= 100 | 5 | | >90 | 20 |
| > 100 | 15 | | >100 | 15 |

The table above shows that two substations do not meet the ComEd's load transfer guidelines of 10 percent. The load transfer capability is greater than 100 percent on 15 of the 182 substations.

ComEd also states that it can transfer the load that can be transferred from these substations in less than 24 hours. ComEd assumes that it initiates switching immediately upon the outage event and that it completes three load transfer operations in an hour.[182] However, in a real emergency, load transfer time would be much longer. As an example, ComEd's response indicates that for Downers Grove approximately 55 percent of the peak load can be transferred to other substations

[179] ComEd evaluates the loss of a single transformer at all substations.
[180] Response to Data Request #51.
[181] Response to Data Requests #27 and #215.
[182] Response to Data Request #215.

with 20 load transfer operations in 7 hours. During the August 10 fire event, ComEd was able to complete the 20 load transfer operations in 23 hours.[183] This suggests that in real situations, 20 load transfer operations are about the maximum within 24 hours. Of the 182 substations listed in the ComEd response, 25 require greater than 20 operations to transfer their transferable load.[184] Other factors to consider are that for conditions that are not at system peak, ComEd could transfer greater loads in shorter periods, and that as load grows, the percentage that ComEd can transfer is smaller unless ComEd constructed new facilities.

### 6. Mobile Equipment

ComEd retains an inventory of mobile equipment that it can use to facilitate the restoration of customers whose electrical service has been lost. ComEd can also rent or lease additional equipment with the exception of portable substation transformers.[185] ComEd stores the larger equipment at a central location and keeps it in a ready status. The Heavy Hauling Department is on call around the clock to transport equipment as required. That department is also responsible to ensure that ComEd observes height and weight requirements for road travel. ComEd keeps one 500 kW generator and some smaller equipment in the operating regions as this equipment is small enough such that local regional hauling equipment can move the equipment. Heavy Hauling has not prescreened substations for potential difficulties in moving equipment to the site.[186]

As the September 2005, the inventory of major portable equipment and its availability is:[187]

[redacted]

[183] Response to Data Request #152.
[184] Three of these substations have greater transfer capability than the load on the substation and may be able to transfer their load in a shorter period of time.
[185] Mobile Equipment Interview of November 2, 2005.
[186] Heavy Hauling Interview of November 17, 2005.
[187] Response to Data Request #38.

ComEd does not use portable generators to meet its planning criteria and does not view portable generators as a good solution to restore service after bus outages because of the number of generators that would be required. It can take approximately 2 hours travel time and 4 to 6 hours hookup time to deploy a generator.[188] ComEd indicated that it is evaluating the number of generators it should have access to on its system; it has scheduled the evaluation for completion by March 2006.[189]

[redacted] ComEd stores the five spare transformers at a central location and has strategically stored spares at other locations when replacements were pending or when transformer testing results indicated a potential problem.[190]

There are no portable low side (15 kV class) transformer or feeder circuit breakers in the portable equipment inventory. Although compliance with the ComEd planning criteria does not require this equipment, ComEd may make use of it if a catastrophic loss of a total substation were to occur. ComEd relies on spare medium voltage breakers that are located across the system. ComEd states that in many cases, actual repairs or the use of spare equipment results in restoration of service to customers as quickly as the use of portable equipment.[191]

## C. Risk-Based Analysis of a Total Substation Loss

### 1. Introduction

This section describes a method to assess the possible effects of a total substation loss and to determine whether there are cost-effective measures that ComEd could take to reduce the vulnerability to such a loss.

ComEd has about 800 substations and, in many ways, each has unique characteristics. Contributing to that uniqueness are things like its function (generation, transmission, or distribution), size, voltage level, specific physical design, availability of spare equipment, geographic location and proximity to other facilities, network configuration, and number of customers served. A thorough vulnerability analysis requires assessing the probability of initiating events, understanding the effects of that event in terms of customer interruptions and interruption durations, and the costs and effects of possible mitigation measures. All of this means that the analysis would be data intensive and would require informed judgments. ComEd does not have a single source reference for the kind of information needed to perform this

[188] Mobile Equipment Interview of December 1, 2005.
[189] Mobile Equipment Interview of December 1, 2005.
[190] Mobile Equipment Interview of December 1, 2005.
[191] Mobile Equipment Interview of December 1, 2005.

vulnerability analysis. Liberty learned that it was not easy for ComEd to gather information about the substation characteristics needed to perform the vulnerability analysis.

The first step in a vulnerability analysis is to rank substations using the sum of the probabilities of initiating events times the total customer-interruption-duration hours. After this prioritization, the analyst can assess the most vulnerable substations in terms of the cost effectiveness of measures that ComEd could take either to reduce the likelihood of the initiating event or to reduce the effects of the substation loss. For example, a substation may rank high in vulnerability because it has a cable-congested cable space. Moving the substation's control cables upstairs or installing a fire suppression system in the cable space each would reduce the probability of a fire causing an extended, total loss of the substation. Constructing additional external tie lines to other substations would reduce the effects of the event by allowing a more timely restoration. Redesigning and rebuilding the substation is another alternative that would eliminate the risk. Appendix B to this report provides a hypothetical example that demonstrates this process.

### 2. Sample Substation Assessment

To demonstrate the start of the analysis process described above, Liberty gathered information about four of ComEd's substations. Appendix C to this report describes the initial information requirements; Liberty presents it here to show the kinds of information that would be required to begin the vulnerability assessment. Appendix D contains the actual information collected on the four sample substations.[192] Liberty chose four substations that were representative of the types of substations on the ComEd system. These were [redacted]. For the purposes of this analysis, Liberty also chose a 24-hour interruption duration.[193] Liberty recognizes that this analysis does not consider important factors such as the amount of time the system is in an off-normal condition after restoration of the substation's customers. The following sections describe Liberty's review of each of these four substations.

[redacted]

The [redacted] substation consists of two 34/13.2 kV transformers and serves approximately 3,000 residential customers and 250 commercial and industrial customers totaling 15.6 MVA of load. No local conditions such as proximity to industrial facilities exist that would put this substation in special jeopardy. There are two overhead distribution feeders emanating from the substation, no inside switchgear, and no cable space.

ComEd has one complete portable transformer unit (PU 921) that is compatible with the transformers at this station. PU 921 is rated 6.25 MVA and does not have the capability to carry the full 15.6 MVA peak load of the substation. However, this portable transformer is in use at

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[192] Response to Data Requests #198 through #201.

[193] Liberty understands that ComEd could restore additional load after the 24-hour period. Liberty did not analyze the likely total outage duration.

[redacted] as of September 16, 2005. ComEd also has the ability to transfer load at this substation. It would take five switching operations to transfer 100 percent of the peak load at the [redacted] substation to other substations. ComEd indicated that it could complete the five switching operations within 2 hours.[194] Even with some delay in the ability to complete these operations, it is likely that ComEd could complete them within Liberty's 24-hour study criterion.

This analysis shows that a more detailed vulnerability assessment of the [redacted] substation is not required.

[redacted]

The [redacted] substation consists of two three-phase 24/30/40 MVA, 132/13.2 kV transformers and two three-phase 20/26.7/33 MVA, 132/13.2 kV transformers and serves approximately 27,100 residential customers and 2,350 commercial and industrial customers totaling 137.3 MVA of load. All of the 138 kV source feeds to [redacted] are in the same right-of-way.[195] The analysis of [redacted] should consider the vulnerability of this right-of-way to accidents by examining its proximity to railroad, highway, and airport facilities.

This substation has 21 feeders, 14 of which terminate on inside switchgear through a cable space and 7 terminate as open-air circuits. The [redacted] substation is similar in design to Downers Grove in that it has a cable space.[196] There is only one three-phase joint in the cable space. The cable space has smoke/heat detectors that are alarmed at the OCC. The DC battery cables are not in proximity to the power cables; however, the DC control cables are above the power cables. Floor penetrations exist in the inside cubicles and in close proximity to the station battery.[197] ComEd has not performed any fire-retardant cable wrapping and the substation does not have any fire suppression system.

ComEd estimates that it can transfer 52.1 MVA of the 137.3 MVA peak load to other substations with 16 load transfer operations in approximately 5 hours.[198] Even considering delays in completing these operations in actual situations, it is likely that ComEd could complete the transfers within Liberty's 24-hour study criterion.

Of the 21 feeder circuits that terminate at this substation, 3 exit the substation as overhead circuits that might lend to common solutions for picking up load near the substation using the portable transformers.[199] In addition, only 1 of the 14 feeder circuits exiting the substation from the cable space becomes accessible within 500 feet of the substation. This indicates that only about 26.2 MVA of load[200] would lend itself to pick-up by transformers, and this assumes that

[194] Response to Data Request #215.
[195] At this point, it is not known if any or all source feeds are on the same electrical structures.
[196] Response to Data Request #16.
[197] While the fact that DC leads may be shielded from a cable space fire, the battery could still be disabled due to the proximity of floor penetrations.
[198] Response to Data Request #215.
[199] Liberty notes that transformers need to be used where ground mats are available for personnel safety during ground faults.
[200] (4/21) x 137.3 MVA.

none of this load was included in the load that ComEd could transfer to other substations above. The remaining 13 circuits would require more individualized solutions due to the distances between the risers and switchgear. Portable generators could provide some additional load relief.

ComEd has in mobile equipment inventory two transformers that are compatible with the four in-service transformers at [redacted]. One is a complete 132/13.2 kV transformer unit (without a low side breaker) that is rated 40 MVA without overload capability. The other is a similar 40 MVA unit; however, as of September 16, 2005, this unit was in service at [redacted].[201]

For a total loss of the [redacted] substation, it appears that on peak load days ComEd could pick up within 24 hours 52.1 MVA of load from other substations, 16.3 MVA with portable transformers, and 10 MW using portable generators. The total of 78.4 MVA equates to an approximate customer count of 16,800. This means that 12,600 customers could remain out of service for more than 24 hours.[202] This analysis suggests that [redacted] should be a candidate for a more detailed assessment and study to determine whether there are cost-effective means to reduce its risk.

[redacted]

The [redacted] substation consists of two three-phase 24/30/40 MVA, 132/13.2 kV transformers and serves approximately 11,100 residential customers and 800 commercial and industrial customers totaling 58.5 MVA of peak load. While no local conditions, such as the proximity to industrial facilities exist that would put the substation in special jeopardy, its design is such that all of its 138 kV source feeds are in the same right-of-way.[203] ComEd should study the vulnerability of this right-of-way as discussed above for [redacted].

This substation has 12 feeders that terminate as open-air circuits. The [redacted] substation is not similar in design to Downers Grove in that it has no cable space.[204]

ComEd estimates that it could transfer 23.6 MVA of the 58.5 MVA load to other substations with 7 load transfer operations in just over 2 hours. As with the [redacted] substation, an actual situation would likely lengthen this transfer time; however it is likely that ComEd could complete the transfers within 24 hours.

Of the 12 feeder circuits that terminate at this substation, 4 are open-air circuits that might lend to common solutions for picking up load at the substation using portable transformers as they exit the substation overhead.[205] In addition, only 1 of the remaining 8 feeder circuits exiting the substation becomes accessible within 500 feet of the substation. This indicates that at most only about 24.4 MVA of load[206] would lend itself to pick-up by transformers. The remaining 7

[201] Response to Data Request #38.
[202] Downers Grove had approximately 8,700 customers without service after 24 hours.
[203] At this point, it is not known if any or all source feeds are on the same electrical structures.
[204] Response to Data Request #16.
[205] Liberty notes that transformers need to be used where ground mats are available for personnel safety during ground faults.
[206] (5/12) x 58.5 MVA.

circuits would require more individualized solutions due to the distances between the risers and switchgear. Portable generators could provide some additional load relief.

ComEd has in mobile equipment inventory two transformers that are compatible with the four in-service transformers at [redacted]. Both are complete 132/13.2 kV transformer units (without a low side breaker) that are rated 40 MVA without overload capability; however, one unit was in service at [redacted] as of September 16, 2005.[207]

For a total loss of the [redacted] substation, it appears that at peak load ComEd could pick up within 24 hours 23.6 MVA of load transferred, 14.6 MVA with transformers outside the substation, and 10 MW using generators. This total of 48.2 MVA equates to about 9,800 customers, meaning that 2,100 customers could remain out of service for more than 24 hours. Because [redacted] does not have a cable space and because the estimated number of customers out of service for more than 24 hours is less than for [redacted], [redacted] should be given a lower priority but nevertheless should be a candidate for a more detailed assessment and study to determine whether there are cost-effective means to reduce its risk.

[redacted]

[redacted] has both a transmission and a distribution substation within the one station yard. One control house serves both substations and both serve load. The distribution substation serves load in the traditional manner and the transmission substation acts as a single source to downstream load. The unique configuration requires that we evaluate each substation component separately.

[redacted]

This substation consists of two three-phase 24/30/40 MVA, 132/13.2 kV transformers and serves approximately 7,500 residential customers and 900 commercial and industrial customers totaling 53.8 MVA of load. While no local conditions, such as the proximity to industrial facilities exist that would put the substation in special jeopardy, its design is such that the source of its DC power is from the adjacent TSS portion of this substation. ComEd should examine the vulnerability of this DC source in more detail.

This substation has nine feeders, all of which terminate on inside switchgear through a cable space. The TDC portion of the [redacted] substation is similar in design to Downers Grove.[208] Five three-phase joints are in the cable space. The cable space has smoke/heat detectors that are alarmed at the OCC. The DC battery cables and the DC control cables are both above and in proximity to the power cables as was the case for Downers Grove. Floor penetrations exist in the inside cubicles, however no penetrations are in close proximity to the station battery. ComEd has not installed fire-retardant cable wrapping or a fire suppression system.

[207] Response to Data Request #38.
[208] Response to Data Request #16.

ComEd estimates that it can transfer the entire 53.8 MVA peak load to other substations with 17 load transfer operations in approximately 6 hours.[209] As with the [redacted] substation, an actual situation would likely lengthen this transfer time; however it is likely that ComEd could complete the transfers within 24 hours.

ComEd has in mobile equipment inventory two transformers that are compatible with the four in-service transformers at [redacted]. Both are complete 132/13.2 kV transformer units (without a low side breaker) that are rated 40 MVA without overload capability.[210]

There would be little usefulness of portable transformers at [redacted]. Besides having 100 percent load transfer capability, only one of the nine circuits exits the substation and has its riser or switchgear within 500 feet of the substation. Loss of this substation would require more individualized solutions due to the distances between the risers and switchgear if ample load transfer capability were not available.

Even though the TDC portion of the [redacted] substation has similar characteristics to Downers Grove, the transfer capability gives this substation a lower priority for a detailed assessment of a total substation outage.

[redacted]

This substation consists of a multitude of 345 kV and 138 kV networked lines. Transformation consists of three three-phase 300 MVA, 330/138 kV transformers and serves approximately 19,100 customers, directly and indirectly. The TDC portion serves approximately 8,700 customers totaling 53.8 MVA of load the TSS portion indirectly serves approximately 10,100 customers totaling 142.8 MVA of load because this substation normally acts as the single source of supply to [redacted]. The total load at this substation is 196.6 MVA. No local conditions exist, such as the proximity to industrial facilities that would put the substation in special jeopardy.

ComEd estimates that it could transfer the entire 196.6 MVA load to other substations within 24 hours.

There are two spare transformers that are compatible with the three in-service transformers, and ComEd has scheduled a third for delivery in May 2006.[211] If ComEd needed these units to restore service to customers, considerable time and additional equipment would be required.

One can reasonably draw the conclusion that ComEd does not need to conduct a more detailed vulnerability assessment of the TSS portion of the [redacted] substation.

[209] Response to Data Request #215.
[210] Response to Data Request #38.
[211] Mobile Equipment Selection Interview of December 1, 2005.

# V. Conclusions and Recommendations

## A. Conclusions

### 1. ComEd's root cause analyses did not address the underlying issues and problems.

ComEd's reports on the four substation cable-space fires did not address important, underlying issues. Had ComEd identified and acted on these issues, it is likely that subsequent events either would not have occurred or would have had less severe consequences. For example, the Pleasant Hill report did not have any recommendation regarding the deteriorated joint that ComEd discovered. The Bartlett report made no recommendation regarding joint installation quality. Neither the Bartlett nor the Schaumburg reports dealt with the matter of the delay in de-energizing the substation. None of the reports addresses the lack of substation fire and emergency plans that could have mitigated consequences. ComEd's report on the Downers Grove fire did not address the important issue of the failure to implement lessons learned from prior events.

### 2. ComEd had, and may still have, problems with the installation quality of cable connectors.

Cable connector installation quality control problems may have existed at Bartlett, Schaumburg, Fisk, and Downers Grove. After the Downers Grove fire, ComEd started infrared inspections of substation cable space joints and found additional workmanship problems.[212]

### 3. ComEd does not have procedures or guidelines for operations, engineering, and construction related to heavy loading on a feeder over an extended period.

To repair a faulty cable, ComEd put the load from feeder W640 on W805. This caused W805 to exceed its normal rating many times during the two months preceding the Downers Grove fire. This loading contributed to the joint failure. However, the loading did not cause ComEd to assign the repair of the W640 cable the highest priority so that it could reduce the loading as soon as possible. Apparently, the frequent alarm at the OCC became an expected event on hot days. While ComEd operated W805 within allowable limits, regularly exceeding the normal limit for the cable did not trigger appropriate ComEd action. This inaction led to accelerated deterioration of an improperly installed joint.

[212] Interview, December 6, 2005, and response to Data Request #225.

### 4. ComEd did not complete all actions identified in earlier substation fire reports.

ComEd's reports on the Pleasant Hill, Bartlett, and Schaumburg fires contained recommendations or mentioned issues that, if completed at Downers Grove, may have prevented the fire, or if the fire occurred, may have limited its consequences. These issues include cable wrapping, sealing floor penetrations, and fire detection systems. The only fire protection improvements fully implemented at Downers Grove were the installation of a fire detection system and marking of hatches to the cable space to keep them closed.

Moreover, ComEd did not fully apply the lessons learned and the lessons that it should have learned from prior substation fire events to Downers Grove. Downers Grove had not been included in ComEd's cable-space improvement programs, it had joints in the cable space not wrapped with fire resistant material, it had open floor penetrations, and it had battery leads routed in the cable space. The Downers Grove incident showed that ComEd did not have a site fire plan, had not trained operators on lessons learned from prior events, and had not pre-planned how to go about switching loads to other substations.

Through its work management and commitment tracking systems, ComEd now has improved tools to help it assure that it completes programs and satisfies recommendations of internal and external reports. However, the frequent re-organizations, personnel transfers, or other factors have caused ComEd to change or reduce the efforts on programs and initiatives brought about by important events. While Liberty believes that ComEd's management is sincere in its current commitments to implement changes to cable-space substations, future events could result in incomplete, or a de-emphasis of, programs.

### 5. The design of substations similar to Downers Grove did not adequately consider the possibility of fires in the cable space.

The routing and layout of power and control cables in the cable space of these substations presents the potential for a fire with significant consequences. The original design did not have fire mitigation qualities. Substations with similarities to Downers Grove are susceptible to fires and outages causing extended customer interruptions. The design has cost advantages over the alternatives and it allows for load growth. However, it concentrates a large number of customers at one point, and ComEd did not adequately protect that point from events like a significant fire.

### 6. ComEd's dispatchers were not responsive to substation fire events.

There were significant delays in de-energizing the substation after the Pleasant Hill, Bartlett, Schaumburg, and Downers Grove fires. During the Downers Grove fire, dispatchers were not attentive to or cognizant of alarms, were not clear how to drop the substation, and were reluctant to do so long after the need should have been obvious.

### 7. There is a significant risk of additional incidents like the Downers Grove fire.

There are at least 103 substations vulnerable to incidents very much like that experienced at Downers Grove. There are large concentrations of customers, suspect cable joints, a lack of fire detection systems, open floor penetrations, control cables in proximity to power cables, and other factors present at these substations.

While Liberty believes that ComEd has taken seriously the Downers Grove incident, ComEd has not yet fully developed a firm, comprehensive, and verifiable cable-space fire-prevention enhancement program. After the Downers Grove fire, ComEd developed and funded a 10-year fire protection strategy that includes fire detection systems and cable space improvements. Initial strategy includes prioritizing fire enhancement efforts on a combination of fire risk and consequences of stranding customers. However, it is not clear that ComEd has identified all of the substations that are at risk. ComEd did not initially include the Medical Center substation, which is a large substation with some PILC and some solid dielectric cables, in its list of cable space substations. There may be other substations with sufficient fire risk to be included on the list of substations for consideration in the fire-protection program.

### 8. ComEd has not considered nor made any contingency plans for the total loss of all substation equipment.

ComEd does not design its power system for the loss of an entire substation, a substation bus, or other severe contingencies without the loss of load. ComEd's distribution planning criteria are comprehensive and consistent with the practices of other utilities. However, ComEd has not studied all of its substations for its exposure to a total substation loss, the consequences of such a loss, or the actions that would be required to recover from such a loss in a reasonable time.[213] The consequences of the Downers Grove fire could have been worse had ComEd not been able to use undamaged equipment in the substation.

## B. Recommendations

### 1. ComEd should assess its own root cause analysis methods and consider obtaining formal root cause training.

More in-depth analyses would help ComEd determine the most effective changes it could make to cure underlying problems. In its determination of these changes, ComEd should not make its recommended actions contingent upon verifying that such action is consistent with common utility practice.

[213] ComEd informed Liberty on 12/15/05 that it had conducted additional studies to determine the effects on load and switching requirements for the loss of 33 major substations. Liberty did not review or verify the results of these analyses.

**2. ComEd should study and improve as required the quality of the training, instructions, and supervision given to personnel who perform critical operations like installing cable connections.**

A properly installed joint should not be the weak link in a cable system. However, ComEd has experienced several instances where poor workmanship or the failure to recognize an unsatisfactory connector installation has caused serious problems. ComEd should require certification of personnel who install cable splices. ComEd should keep records of joint construction to augment other means of accountability in the workplace.

**3. ComEd should develop guidelines for dealing with heavily loaded feeder systems.**

Had operations made engineering and construction aware of the frequent heavy loading on feeder W805, ComEd could have changed the priority of the work on the transferred feeder or possibly redistributed the load. The frequent alarm on circuit W805, and particularly phase C of that circuit, became almost expected conditions to dispatchers. They did not communicate any expectation of expediency to others within ComEd because there was no instruction to do so.

**4. ComEd should continue to inspect, evaluate, and implement changes at substations with vulnerabilities to fires like those that have occurred in the past.**

ComEd should evaluate substations that are similar in design to Downers Grove to determine which have the potential to result in long duration outages to a large number of customers. ComEd should implement the lessons learned from the Downers Grove and other earlier fires in a manner that mitigates this potential loss of service to customers.

ComEd should continue and complete as soon as practical its infrared inspections of joints in cable spaces.

ComEd should develop a formal method for prioritizing cable-space fire-protection enhancements to reduce the outage risks caused by cable space fires. ComEd should determine the timeliness and cost-effectiveness of various options to reduce quickly the most vulnerable substations. For example, wrapping joints in a substation with a low transfer capacity and serving a large number of customers may be more cost-effective that doing full enhancements at several smaller substations with higher transfer capacities.

**5. ComEd should improve dispatcher and operator training and qualifications related to substation fires.**

ComEd should train its area operators and dispatchers in communicating in a clear and concise manner and in the capabilities of system components and their operation during off-normal conditions. Off-normal conditions include substation fires where normal controls may not be available or situations where personnel need to use emergency equipment capabilities.

ComEd should instill in its dispatchers the expediency of returning system configurations to normal, de-energizing equipment under proper circumstances, acknowledging alarms, and absolute decision-making authority over the areas of the system for which they have jurisdiction. This training would include TSO dispatchers who no longer exert jurisdiction of distribution equipment.

ComEd should train Customer Service Representatives to be clear about whether a structure fire exists.

ComEd should re-evaluate the priority given to substation fire alarms and the actions that dispatchers should take after receiving such an alarm. ComEd should raise the priority given to fire events by including on-site accessible fire plans and a direct access number to the dispatcher for fire personnel. ComEd should develop mechanisms that would reduce the verification time in determining that a fire exists at one of its substations.

**6. ComEd should conduct a risk-based analysis of all substations and make appropriate plans for the recovery of substations assuming a total loss of all substation equipment.**

ComEd should review all of its substations, perhaps in the manner that Liberty developed, to identify substations that may be vulnerable to extended customer outages and the possible causes of those outages. Liberty is not suggesting here that ComEd design its system so that it could easily transfer the load of every substation to another. However, ComEd should know where the system is vulnerable and have at least conceptual plans for dealing with a total substation loss. As part of this review, ComEd should review its portable equipment inventory to determine if additional equipment in this inventory would be beneficial.

For all of the above recommendations, ComEd should present a plan of accomplishment to the ICC and support some means for the ICC to verify actual progress against that plan.

# Appendix A – RCA Timeline

| Date / Time | Event |
|---|---|
| 12/27/93 8:56 | Pleasant Hill; two feeder circuit breakers automatically tripped and locked out. |
| 12/27/93 9:22 | Area operators arrived on site; a third circuit breaker automatically tripped. |
| 12/27/93 9:28 | A fourth circuit breaker automatically tripped. |
| 12/27/93 9:37 | ComEd lost supervisory control. |
| 12/27/93 9:42 | ComEd called the fire department. |
| 12/27/93 9:56 | Fire department arrived on site. |
| 12/27/93 10:45 | ComEd used remote switching to de-energize the incoming 138 kV lines. |
| 12/27/93 13:20 | All Pleasant Hill customers restored. |
| 2/16/94 0:00 | Pleasant Hill Substation, TDC 595 Fire Report issued. |
| 7/18/96 22:42 | The first feeder circuit breaker tripped and locked out. Bartlett. |
| 7/18/96 22:51 | Nine additional feeders faulted and their breakers locked out. |
| 7/18/96 23:00 | A substation construction supervisor arrived on site. |
| 7/18/96 23:08 | ComEd called the fire department. |
| 7/18/96 23:57 | Circuit switchers opened locally to de-energize substation. |
| 7/19/96 21:07 | All Bartlett customers restored. |
| 10/24/96 0:00 | Bartlett Substation, TDC 574 Fire Investigation Report issued. |
| 8/15/01 12:51 | Fire alarm and then a 12 kV feeder breaker trip alarm. Schaumburg |
| 8/15/01 13:15 | Area operator arrived on site and found cable space filled with smoke. |
| 8/15/01 13:45 | Substation construction and underground crews arrived on site. |
| 8/15/01 13:46 | Another 12 kV feeder circuit breaker tripped. |
| 8/15/01 14:30 | ComEd called the fire department; arrived on site about three minutes later. |
| 8/15/01 15:14 | ComEd de-energized the substation. |
| 8/15/01 15:55 | Fire extinguished. |
| 8/15/01 23:37 | All Schaumburg customers restored. |
| 5/27/05 0:00 | New station battery commissioned at TDC 580. |
| 5/29/05 0:00 | W640 experiences cable fault, load transferred to W805 at TDC 580. |
| 6/10/05 0:00 | W805 phase C exceeds normal limit 1700 - 1800 hours (1 hour). |
| 6/23/05 0:00 | W805 phase C exceeds normal limit 1600 - 2000 hours (4 hours). |
| 6/24/05 0:00 | W805 phase C exceeds normal limit 1200 - 2200 hours (10 hours). |
| 6/24/05 20:37 | Fire at Fisk Substation, STA 11. |
| 6/24/05 21:36 | Fisk Substation de-energized, dropping 51,000 customers. |
| 6/25/05 0:00 | W805 exceeds normal limit 1200 - 1900 hours (7 hours). |
| 6/25/05 21:15 | All Fisk customers restored. |

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|---|---|
| 6/26/05 0:00 | W805 phase C exceeds normal limit 1300 - 2000 hours (7 hours). |
| 6/27/05 0:00 | W805 phase C exceeds normal limit 1200 - 2200 hours (10 hours). |
| 6/28/05 0:00 | W805 phase C exceeds normal limit 1500 - 1900 hours (4 hours). |
| 6/29/05 0:00 | W640 cable repaired, fails VLF test. |
| 6/30/05 0:00 | W640 cable repaired, fails VLF test. |
| 7/17/05 0:00 | W805 phase C exceeds normal limit 1300 - 2200 hours (9 hours). |
| 7/18/05 0:00 | W805 phase C exceeds normal limit 1300 - 1900 hours (6 hours). |
| 7/19/05 0:00 | W805 phase C exceeds normal limit 1500 - 1900 hours (4 hours). |
| 7/24/05 0:00 | W805 phase C exceeds normal limit 1100 - 2300 hours (12 hours). |
| 7/31/05 0:00 | W805 phase C exceeds normal limit 1600 - 1800 hours (2 hours). |
| 8/1/05 0:00 | W805 phase C exceeds normal limit 1400 - 2300 hours (9 hours). |
| 8/2/05 0:00 | W805 phase C exceeds normal limit 1200 - 2200 hours (10 hours). |
| 8/3/05 0:00 | W805 phase C exceeds normal limit 1100 - 2200 hours (11 hours). |
| 8/4/05 0:00 | W805 phase C exceeds normal limit 1600 - 2200 hours (6 hours). |
| 8/5/05 0:00 | W640 cable fault repaired, fails VLF test. |
| 8/8/05 0:00 | W805 phase C exceeds normal limit 1300 - 2200 hours (9 hours). |
| 8/9/05 0:00 | W805 phase C exceeds normal limit 1200 - 2200 hours (10 hours). |
| 8/10/05 0:00 | W805 phase C exceeds normal limit 1300 - 1700 hours (4 hours). |
| 08/10/05 16:31:02 | OCC Load Dispatcher receives W805 Trip Alarm - Priority #1. |
| 08/10/05 16:31:11 | OCC Load Dispatcher receives TDC 580 Fire alarm - Priority #2. |
| 8/10/05 16:33 | Significant number of trouble calls start for W805 outage (Bus #1). |
| 8/10/05 16:37 | Joliet Area Operator (AO) calls LD to check out. Talks about school. |
| 8/10/05 16:38 | LD calls AO. SCADA down and W805 out. AO will check out. |
| 8/10/05 16:38 | LD calls Engineering Assistant (EA). W805 lockout at 16:31 |
| 08/10/05 16:39:26 | TSO receives loss of channel alarm for L1803 and L1809 at TDC 580. |
| 08/10/05 16:39:26 | SCADA lost at TDC 580. |
| 8/10/05 16:40 | W8020 burns open, causes bus fault on Bus #5, all breakers open, W803 and W8017 open. |
| 8/10/05 16:40 | DC control circuit short, Bus #2 trip, all DC breakers open, W806 and W807 open. |
| 8/10/05 16:40 | Individual faults or bus differential open W8001, W8002, W802, and W804 on Bus #1. |
| 08/10/05 16:40:59 | DC lost at TDC 580. |
| 8/10/05 16:41 | OD calls Overhead Electrician (OE). W805 locked out. No tickets seen. Go to first open point-51396. |
| 8/10/05 16:43 | Power spike observed at TSO on 138 kV at [redacted]. |
| 8/10/05 16:43 | Significant number of trouble calls start for W8001 outage (Bus #1). |
| 8/10/05 16:43 | Significant number of trouble calls start for W8002 outage (Bus #1). |
| 8/10/05 16:43 | Significant number of trouble calls start for W8017 outage (Bus |

| | |
|---|---|
| | #5). |
| 8/10/05 16:43 | Significant number of trouble calls start for W802 outage (Bus #1). |
| 8/10/05 16:43 | Significant number of trouble calls start for W8020 outage (Bus #5). |
| 8/10/05 16:43 | Significant number of trouble calls start for W803 outage (Bus #5). |
| 8/10/05 16:43 | Significant number of trouble calls start for W807 outage (Bus #2). |
| 8/10/05 16:43 | OD calls OE. Go to tie point-83219. |
| 8/10/05 16:44 | Significant number of trouble calls start for W804 outage (Bus #1). |
| 8/10/05 16:44 | Significant number of trouble calls start for W806 outage (Bus #2). |
| 08/10/05 16:44:38 | Fire Department receives call – smoke coming from TDC 580. |
| 08/10/05 16:45:50 | Fire Department arrives at TDC 580. |
| 8/10/05 16:47 | OD calls two OEs. Lost SCADA. Enough tickets that bus was lost. TM heads towards station. |
| 8/10/05 16:54 | FD calls ComEd, reports S/S on fire, requests ETA + callback, logged by CSR. |
| 8/10/05 16:57 | TSO calls LD. TSO has received channel status alarm at TDC580. |
| 8/10/05 17:00 | SRM Team B activated. |
| 8/10/05 17:05 | Operator on site reports station on fire. |
| 8/10/05 17:05 | The Area Operator asks the Load Dispatcher for permission to dump TDC580 locally. |
| 8/10/05 17:07 | LD calls TSO. TDC580 on fire. TSO gives OCC permission to de-energize TDC580. |
| 8/10/05 17:07 | OES calls OD. Station on fire. |
| 8/10/05 17:15 | Approximate time of arrival of SPOC. |
| 8/10/05 17:17 | LD calls TSO. OCC requests 138 kV lines to be "dumped if possible." |
| 8/10/05 17:21 | TSO calls LD. TSO wants 12 kV open at TDC580. LD says he cannot. |
| 8/10/05 17:23 | LD calls TSO. OCC will get the operator on the line. |
| 8/10/05 17:24 | LD calls TSO and Area Operator. Area Operator explains situation. |
| 8/10/05 17:25 | LD requests TSO to open circuit switchers at [redacted]. |
| 8/10/05 17:27 | OCC Shift Manager requests TSO to dump TDC580. |
| 08/10/05 17:28:26 | TSO opens Circuit Swr. 0314 [redacted] at [redacted]. |
| 08/10/05 17:28:26 | W8019 (B#1) and W808, W809, W8010, and W8011 (B#3) dropped. |
| 08/10/05 17:28:40 | TSO opens Circuit Swr. 0909 [redacted] at [redacted]. |
| 08/10/05 17:28:40 | W8012, W8013, W8014, and W8015 (B#4) dropped. |
| 8/10/05 17:29 | TSO confirms TDC 580 de-energized, dropping remaining customers. |
| 8/10/05 17:31 | Circuit Switchers [redacted] and [redacted] at TDC580 opened and decoupled. |
| 8/10/05 17:52 | FD extinguishes fire for the first time. |
| 8/10/05 18:00 | Approximate time of arrival of ERD. |

| | |
|---|---|
| 8/10/05 18:40 | 40% of load restored on W8002 via J925 - DCJ 92, Lemont. |
| 8/10/05 18:40 | 40% of load restored on W8015 via W3625 - TSS136, Burr Ridge. |
| 8/10/05 19:00 | 100% of load restored on W8015, via W386 - DCW38, DG Township. |
| 8/10/05 19:00 | SRM Team B arrived on site. |
| 8/10/05 19:02 | Partial access to control house given to ComEd by Fire Dept. |
| 8/10/05 19:03 | ComEd personnel escorted from S/S by FD due to CO alarm. |
| 8/10/05 19:05 | 50% of load restored on W8017 via W031 - TSS103, Lisle. |
| 8/10/05 19:15 | 100% of load restored on W8017 via W039 - TSS 103, Lisle. |
| 8/10/05 19:35 | Upfeeds opened per OCC log - OCC states cable space is safe for entry. |
| 8/10/05 19:42 | Restricted access to control house because of lead contamination. |
| 8/10/05 19:50 | 100% of load restored on W8001 via W595 - TDC559, Woodridge. |
| 8/10/05 19:53 | Fire restarted. |
| 8/10/05 20:15 | 30% of load restored on W8014, via W6122 - TDC561, Bolingbrook. |
| 8/10/05 20:25 | 100% of load restored on W8014 via W617 - TDC561, Bolingbrook. |
| 8/10/05 20:55 | 50% of load restored on W805 via W3613 - TSS136, Burr Ridge. |
| 8/10/05 21:00 | Fire extinguished – second time. |
| 8/10/05 21:05 | 75% of load restored on W806 - via W3607 - TSS136, Burr Ridge. |
| 8/10/05 21:30 | 100% of load restored on W8019 via W6125 - TDC561, Bolingbrook. |
| 08/10/05 21:38:40 | Fire Department turns TDC 580 over to ComEd and leaves site. |
| 8/10/05 23:50 | 75% of load restored on W8011, via W036 - TSS103, Lisle. |
| 8/10/05 23:58 | 100% of load restored on W805 via W640 - DCW640, Tri State Village. |
| 8/11/05 1:00 | 50% of load restored on W8020 via J925 - DCJ92, Lamont. |
| 8/11/05 1:11 | 100% of load restored on W8011 via W591 - TDC559, Woodridge. |
| 8/11/05 1:30 | 50% of load restored on W8012, via W4572 - TSS145, York Center. |
| 8/11/05 2:00 | SRM Team C arrived on site. |
| 8/11/05 2:00 | SRM Team decision log initiated. |
| 8/11/05 2:00 | [redacted] - W8002 - Restored via 2 Meg gen. |
| 8/11/05 2:20 | 66% of load restored on W807 via W387 - DCW38, DG Township. |
| 8/11/05 2:45 | SRM Team open items log initiated. |
| 8/11/05 3:30 | SRM Team B to Team C turnover completed. |
| 8/11/05 4:45 | Fairview Apts. - Restored via 2 Meg gen. |
| 8/11/05 7:00 | [redacted] - W8013 - Restored via 2 Meg gen. |
| 8/11/05 10:45 | [redacted] - W8013 - Restored via 2 Meg gen. |
| 8/11/05 11:20 | 25% of load restored on W802 via generator. |
| 8/11/05 12:40 | 100% of load restored on W806 via W3607 - TSS136, Burr Ridge. |

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|---|---|
| 8/11/05 14:00 | SRM Team B arrived at site. |
| 8/11/05 14:53 | 100% of load restored on W807 via W387, DCW38, DG Township. |
| 8/11/05 14:55 | 100% of load restored on W8012 via W419 - SS558, Westmont. |
| 8/11/05 15:30 | SRM Team C to Team B turnover completed. |
| 8/11/05 15:58 | 100% of load restored on W8013 via W3625 - TSS136, Burr Ridge. |
| 8/11/05 15:58 | [redacted] - W808 - Restored via 500 kW gen. |
| 8/11/05 16:20 | 99% of load restored on W8020 via J925 - DCJ92, Lemont. |
| 8/11/05 19:15 | 50% of load restored on W803 via W595 - TDC559, Woodridge. |
| 8/11/05 19:45 | [redacted] - W804 - Restored via 500 kW gen. |
| 8/11/05 20:27 | 100% of load restored on W8002 via W3625 - TSS136, Burr Ridge. |
| 8/11/05 20:45 | [redacted] - W802 - Restored via 500 kW gen. |
| 8/12/05 2:00 | Team C arrived on site. |
| 8/12/05 3:30 | SRM Team B to Team C turnover completed. |
| 8/12/05 4:30 | 100% of load restored on W803 via W595 - TDC559, Woodridge. |
| 8/12/05 4:45 | W803 - 2 Meg gen installed to help with loading. |
| 8/12/05 8:42 | 100% of load restored on W8020 via W3625 - TSS136 Burr Ridge. |
| 8/12/05 12:00 | SRM Team D arrived on site. |
| 8/12/05 12:35 | Bus #3 livened. |
| 8/12/05 13:00 | 100% of load restored on W808 via Bus #3 - TDC580, Downers Grove. |
| 8/12/05 13:29 | 100% of load restored on W802 via W808 - TDC580, Downers Grove. |
| 8/12/05 13:30 | SRM Team C to Team D turnover completed. |
| 8/12/05 13:36 | 100% of load restored on W809 via Bus #3 - TDC580, Downers Grove. |
| 8/12/05 13:36 | 100% of load restored on W804 via W809 - TDC580, Downers Grove. |
| 8/12/05 13:45 | 100% of load restored on W8010 via Bus #3 - TDC580, Downers Grove. |
| 8/12/05 13:45 | All load restored at TDC 580, Downers Grove. |
| 8/13/05 0:00 | SRM Team C arrived on site. |
| 8/13/05 1:00 | SRM Team D to Team C turnover completed. |
| 8/13/05 12:00 | SRM Team D arrived on site. |
| 8/13/05 13:00 | SRM Team C to Team D turnover completed. |
| 8/13/05 20:22 | SRM Team D stands down. |
| 8/14/05 0:00 | TDC 580 turned over to project management. |
| 8/31/05 0:00 | Fisk Substation Fire Root Cause Investigation Report issued. |
| 9/12/05 0:00 | W640 cable replaced. |
| 10/31/05 0:00 | Downers Grove Root Cause report issued. |

# Appendix B – Example of Substation Assessment

A simplified hypothetical example may be helpful to demonstrate the framework of the vulnerability analysis described in the body of this report. Assume that one of the total substation loss events is a fire in the cable space of substation TDC-911. The probability of occurrence is 0.005 events per year.[214] TDC-911 serves 30,000 customers (4 kVA per customer or 120 MVA) with four 40 MVA transformers and has 30 circuits. TDC-911 can switch 20 percent of its peak load (6,000 customers) to other substations within 24 hours over 8 interconnections. There are three mobile 2 MW generators belonging to the utility and another three mobile 2 MW generators that the utility can rent. The utility can install all the generators within 24 hours, picking up 3,000 customers. Therefore, it can pick up 9,000 customers in 24 hours. The utility has not installed fire suppression nor wrapped cables.

Application of the formula probability times number of customers without service at the 24-hour duration point results in this event receiving a raw score of 105.0. The utility can mitigate the event by variety of actions. It could move control cables upstairs, reducing the probability of event occurrence by 50 percent. It could install a fire suppression system, reducing the probability of event occurrence by a factor of 10. It could install four new circuit interconnections with other substations, reducing the number of affected customers by 3,000, or it could rebuild the entire control house, reducing the probability of event occurrence and customer effect to zero. The table below shows these results and compares mitigation actions on a dollar per point basis that reduced the raw score of 105.0.

**First Evaluation of Mitigation Measures**

| Mitigation of | Project | Cost | New Event Probability | New Customer Impact | New Score | Ranking $/Point Reduced |
|---|---|---|---|---|---|---|
| Probability | Move Control Cables Upstairs | $380,000 | .005x.50=.0025 | 21,000 | 52.5 | $7,238 |
| Probability | Install Fire Suppression System | $150,000 | .005x.10=.0005 | 21,000 | 10.5 | $1,587 |
| Impact | Install 4 new Interconnections with Other Substations | $40,000* | .005 | 18,000 | 90.0 | $1,333 |
| Risk Event | Rebuild Substation Control House | $3.5 M | .000 | 0 | 0.0 | $33,333 |

* The cost estimate considered the benefits to the connecting substations.

This analysis shows that the installation of the four new interconnections is the most economical route on which to proceed. The process is now requires recalculation of the scores assuming those four new interconnections are installed. The installation reduced the customer effect to 18,000 customers and the resultant raw score to 90.0. The table below shows the results of the next step.

[214] ComEd has similar substations with a total 1,500 circuits and there has been a cable space fire every four years. The probability is (30/1500)/4 = 0.005.

## Evaluation of Mitigation Measures

| Mitigation of | Project | Cost | New Event Probability | New Customer Impact | New Score | Ranking $/Point Reduced |
|---|---|---|---|---|---|---|
| Probability | Move Control Cables Upstairs | $380,000 | .005x.50=.0025 | 18,000 | 45.0 | $8,444 |
| Probability | Install Fire Suppression System | $150,000 | .005x.10=.0005 | 18,000 | 9.0 | $1,852 |
| Risk Event | Rebuild Substation Control House | $3,500,000 | .000 | 0 | 0.0 | $38,888 |

Because the installation of a fire suppression system is still relatively inexpensive and there is a wide gap to the rankings of the other alternatives, the utility may also decide to make this change. One could also make these decisions by the establishment of a maximum score for any event regardless of cost.

# Appendix C – Information for Substation Assessment

Please provide the following information for each substation on the ComEd system. If a substation serves more than one function (G, T, or D as defined in part b. below), supply a separate response for each.

a. Identification number (e.g., TDC-580)(must be filled out for each row of data)
b. Classification by (G) generation (directly connected generation), (T) transmission (no distribution load directly served), or (D) distribution (load directly fed) station
c. Location (address and city or town)
d. Operating Region as (C) Chicago, (N) Northern, (W) West, or (S) South
e. Service Center (unique three letter geographic abbreviation)
f. Is an airport located within ½ mile of the substation? (Y/N)
g. Is a significant potentially destructive industrial facility such as a chemical plant located within ½ mile of the substation? (Y/N)
h. Number of airport or destructive industrial facilities within ½ mile of the substation
i. Are public roads or roads accessible to the public in direct proximity to the substation? (Y/N)
j. Estimate of distance from public road to the substation control house (feet)
k. Is substation in or next to a high rise building (Y/N)
l. Is switchgear below grade (Y/N)
m. Has vandalism that caused an outage occurred at the substation within the last 5 years? (Y/N)
n. Has vandalism that caused an outage occurred at the substation within the last 10 years? (Y/N)
o. Is the substation located in a 100-year flood plain? (Y/N)
p. Is a fire department station located within ½ mile of the substation? (Y/N)
q. Is the closest fire department station manned full time? (Y/N)
r. Are all high voltage feeds either radial, on the same tower, or in the same right-of-way/duct/street? (Y/N)
s. Is substation fed from a single substation? (Y/N)
t. If the substation is fed from a single substation, please list that substation by its substation identification number as identified in part a. above
u. Number of power transformers in service in the substation
v. Number of power transformers in service that are located indoors
w. For each in-service power transformer in the substation, list its multiple MVA nameplate rating (MVA)
x. For each in-service power transformer in the substation, list its high voltage winding voltage rating (kV)
y. For each in-service power transformer in the substation, list its low voltage winding voltage rating (kV)

z. Is each power transformer three-phase or single-phase (3/1)?

aa. Are oil circuit breakers in close proximity to each other (like Jefferson used to be)? (Y/N)

bb. Number of station battery banks

cc. If more than one battery bank, are they in separate rooms or greater than 10 feet apart? (Y/N)

dd. Number of control buildings

ee. If the control building serves more than one separated substation yard, list the additional substation yards by their substation identification number as identified in part a. above

ff. For each control house, are there smoke/heat detectors in the control house main floor(Y/N)?

gg. For each control house, are the control house main floor smoke/heat detectors alarmed on SCADA? (Y/N)

hh. For each control house, is there a fire suppression system in the control house main floor? (Y/N)

ii. For each control house, is the control house main floor fire suppression system alarmed on SCADA? (Y/N)

**For each substation identified as "G" in part b. above, additionally provide:**

jj. Are any dedicated spare power transformers (other than step up or auxiliary) kept for this station? (Y/N)

kk. The number of dedicated spare power transformers (other than step up or auxiliary) kept

ll. For each dedicated spare power transformer (other than step up or auxiliary), list its stored location by its substation identification number as identified in part a. above

mm. For each dedicated spare power transformer (other than step up or auxiliary), list its multiple MVA nameplate rating (MVA)

nn. For each dedicated spare power transformer (other than step up or auxiliary), list its high voltage winding voltage rating (kV)

oo. For each dedicated spare power transformer (other than step up or auxiliary), list its low voltage winding voltage rating (kV)

pp. Estimate the number of days to install a dedicated spare transformer

qq. Estimate of the number of customers that would be without service for the sudden loss of the entire substation

rr. Estimate of the 2005 coincident peak MVA of load that would be interrupted for the sudden loss of the entire substation (MVA)

ss. If any MVA load would be lost at peak as a result of the sudden loss of the entire substation, estimate the amount of load that could be transferred to other substations within 24 hours (MVA)

**For each substation identified as "T" in part b. above, additionally provide:**

tt. Are any available spare power transformers kept for this station? (Y/N)

uu. The number of available spare power transformers kept

vv. For each available spare power transformer, list its stored location by its substation identification number as identified in part a. above

ww. For each available spare power, list its multiple MVA nameplate rating (MVA)

xx. For each available spare power transformer, list its high voltage winding voltage rating (kV)

yy. For each available spare power transformer, list its low voltage winding voltage rating (kV)

zz. Estimate the number of days to install an available spare power transformer

aaa. Estimate of the number of customers that would be without service for the sudden loss of the entire substation

bbb. Estimate of the 2005 coincident peak MVA of load that would be interrupted for the sudden loss of the entire substation (MVA)

ccc. If any MVA load would be lost at peak as a result of the sudden loss of the entire substation, estimate the amount of load that could be transferred to other substations within 24 hours (MVA)

**For each substation identified as "D" in part b. above, additionally provide:**

ddd. Estimated 2005 coincident peak load (MVA)

eee. Estimated number of rolled up residential customers at the time of the substation 2005 peak with the substation in its normal configuration

fff. Estimated number of rolled up commercial and industrial customers at the time of the substation 2005 peak with the substation in its normal configuration

ggg. Identify any additional substations directly fed by this substation by their substation identification numbers as identified in part a. above.

hhh. Estimate the amount of load at peak that could be transferred to other substations within 24 hours (MVA)

iii. Number of load transfer operations to transfer load

jjj. Estimated load at peak that could be transferred to other substations within 24 hours modified for actual experience (MVA)

kkk. For each in-service power transformer in the station, indicate whether it is equipped for mobile ready replacement (restore in less than 24 hours) (Y/N)

lll. For each in-service power transformer in the station, list the Portable Unit Transformer equipment numbers (from the response to DR #38) of compatible transformers

mmm. For each in-service power transformer in the station, and assuming a total station outage and no usable substation components remain, list what other portable equipment numbers (from the response to DR #38) would be required to totally restore service at peak load

nnn. Estimated time to deliver portable equipment from inventory (Hours)

ooo. Other major equipment needed for restoration that is not in the portable equipment inventory.

ppp. For each in-service power transformer in the station, and assuming a total station outage at peak and no usable substation components remain, estimate the number of days to procure and install equipment that is not available from the portable equipment inventory.

qqq. Number of circuits feeding customers

rrr. Number of circuit terminating on inside switchgear

sss. Number of circuits terminating on outside switchgear

ttt. Number of circuits terminating on open air equipment

uuu. Number of circuits that exit overhead

vvv. Number of circuits with exit risers >500 feet from substation

www. Number of underground circuits with switchgear >500 feet from substation

xxx. Number of inside switchgear cubicles that are in-service

yyy. Number of inside switchgear cubicles that are for future use

zzz. Number of outside switchgear cubicles

aaaa. Number of outside switchgear cubicles with animal protection

bbbb. Number of open air circuit breakers/reclosers

cccc. Number of open air circuit breakers with animal protection

dddd. Number of feeders with reclosing enabled

eeee. Number of feeders terminating in inside switchgear with reclosing enabled

ffff. Number of feeder circuits located in the cable space

gggg. Are there smoke/heat detectors in the cable space? (Y/N)

hhhh. Are the cable space smoke/heat detectors alarmed on SCADA? (Y/N)

iiii. Is there a fire suppression system in the cable space? (Y/N)

jjjj. Is the cable space fire suppression system alarmed on SCADA? (Y/N)

kkkk. The number of joints (set of three equals one joint) in the cable space

llll. The number of joints (set of three equals one joint) in the cable space wrapped with fire-retardant material

mmmm. If joint is wrapped, are adjacent cables wrapped? (Y/N)

nnnn. Are the main DC cables at an elevation higher than the power exit cables without a concrete floor between them? (Y/N)

oooo. Are the main DC cables within 10 feet (horizontally) of the power exit cables? (Y/N)

pppp. Are the control cables at an elevation higher than the power exit cables without a concrete floor between them? (Y/N)

qqqq. Are the control cables within 10 feet (horizontally) of the power exit cables? (Y/N)

rrrr. Are there unfilled floor penetrations in inside switchgear cubicles? (Y/N) ssss. Are there unfilled floor penetrations or floor hatches within 10 feet of battery bank(s)? (Y/N)

# Appendix D – Substation Database

| | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| rev. | 12/7/2005 | a | b | c | d | e | f | g | h | I | j | k | l | m | n | o | p | q | r | s | t | u | v | w | x | y | z |
| DR# | | ID | Class | Location | Operating Region | Service Center | Airport | Industy Facility | # | Roads | Distance from Road (approx) | Sub in or next to Hi-Rise? | Swgr below grade | Vandal 5 year | Vandal 10 year | 100 year Flood | F.D. | F.D. Manned | High Voltage Feeds | Single Sub. | ID | X-fmr | X-fmr Indoor | X-fmr MVA | X-fmr High kV | X-fmr Low kV | X-fmr3/1 |
| [redacted] | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | NA = Not Applicable | | | | | | | | | | | | | | | | | | | | | | | |

LIBERTY MASTER DATA REQUEST FOR SUBSTATION INFORMATION 2005

| | | | | | | | | | | | Substations Identified as "G" | | | | | | | | | | Substations Identified as "T" | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| rev. | 12/7/2005 | aa | bb | cc | dd | ee | ff | gg | hh | ii | jj | kk | ll | mm | nn | oo | pp | qq | rr | ss | tt | uu | vv | ww | xx | yy | zz | aaa | bbb |
| DR# | | OCB Close | Batt. Bank | Batt. Sep | # Control | Addnl ID | Detect. | Detect. SCADA | Suppress. | Sup. SCADA | Spare X-fmr | # Spare X-fmr | Location | X-fmr MVA | X-fmr High kV | X-fmr Low kV | Days | # Cus. | 05 Peak | Transfer | Spare X-fmr | # Spare X-fmr | Location | X-fmr MVA | X-fmr High kV | X-fmr Low kV | Days (Est) | # Cus. (Est) | T 05 Peak (Est) |
| [redacted] | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

LIBERTY MASTER DATA REQUEST FOR SUBSTATION INFORMATION 2005

| | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Substations Identified as "I | | | | | | | | | | | | | | | | | | | | | |
| rev. | 12/7/2005 | ccc | ddd | eee | fff | ggg | hhh | iii | jjj | kkk | lll | mmm | nnn | ooo | ppp | qqq | rrr | sss | ttt | uuu | vvv | www | xxx | yyy | zzz |
| DR# | | Transfer (Est) | D 05 Peak (Est) | # Res. (Est) | # C & I (Est) | Subs Fed | Transfer (Est) | # of Switch Ops | Liberty's Mod. Est Transfer Load | Mobile-R | PUT # | Port Other | Est. Delivery Time for Portable Equip. | Other Major Equip. | Days (Est) | Circuits Feeding Cust. | Inside Swgr (Circuits) | Outside Swgr (Circuits) | Open Air (Circuits) | # of Ovhd Exit Ckts. | # Riser Ckts > 500' from Sta | # Ung Ckts with Swgr > 500' from Sta | Inside Swg (in service) | Inside Swg (future) | Outside Swg |
| [redacted] | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | | | | |

| | | D" | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| rev. | 12/7/2005 | aaaa | bbbb | cccc | dddd | eeee | ffff | gggg | hhhh | iiii | jjjj | kkkk | llll | mmmm | nnnn | oooo | pppp | qqqq | rrrr | ssss |
| **DR#** | | **Outside Animal Prot.** | **Open Air Brkr/Rec** | **Open Air Animal Prot.** | **Reclose Enabled** | **Reclose Enabled (Inside)** | **CS Fdrs** | **CS Detect** | **CS Detect SCADA** | **CS Suppres s** | **Supres s SCADA** | **Joints** | **Wrap** | **Adj Cbls** | **DC Cable** | **DC 10 ft** | **Cont. Floor** | **Cont. 10 ft** | **Penetrations** | **Bat. Penetrations** |
| [redacted] | | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | |